FINAL REPORT

Contract NAS 9-10484

EXTENDABLE NOZZLES FOR SPACE ENGINES

Volume II· Design Guide

Report 10484-FR   November 1970
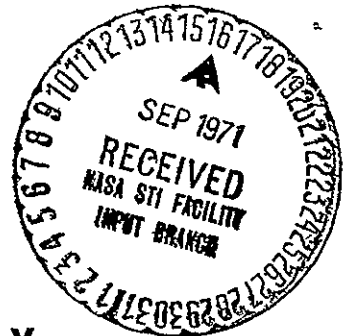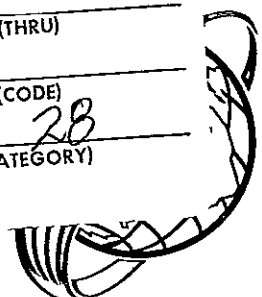
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.

FINAL REPORT

EXTENDABLE NOZZLES FOR SPACE ENGINES

VOLUME II   DESIGN GUIDE

Report 10484-FR

November 1970

Prepared Under

Contract NAS 9-10484

FOREWORD

This report is submitted in partial compliance with the requirements of Contract 9-10484 as Volume II of the program final report   It's purpose is to provide guidelines for the design of extendable nozzles for space engines

All work under the subject contract was performed for the National Aeronautics and Space Administration's Manned Spacecraft Center, Houston, Texas, by the Aerojet Liquid Rocket Company   The program was under the direction of Dr N E Van Huff, program manager, R C Schindler, project manager, and E Schmauderer, project engineer   The NASA project engineer for the program is Mr G Hubbard

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I   INTRODUCTION

    A   SCOPE

        This report is intended as a guide for the design of extendable – retractable nozzles for space engines   The information presented is based on the experiences of Aerojet Liquid Rocket Company and the industry, and detailed investigation and analysis conducted on this program, Contract NAS 9-10484 Optimized techniques of nozzle translation, alignment, sealing and cooling as well as nozzle performance and thermal design data are presented for use in the design of a deployable nozzle

        The engine operating conditions specified by the contract statement of work, established the use limits of the data presented in this document They are as follows

        Chamber Pressure (P_c) 300 psia to 800 psia

        Thrust (F)   5,000 lb to 20,000 lb

        Nozzle Expansion Ratio (ε) 50 1 to 300 1

        In addition to establishing the design use limits, the specified engine operating conditions were used in conjunction with information derived from the program studies to establish operating conditions for a deployable nozzle engine system   These operating conditions are presented in Section II Design objectives and requirements, conforming to the engine system operating conditions, were formulated to assist in the definition of optimized translation, alignment, sealing and cooling techniques

        The design objectives and requirements best satisfying the specified engine system operating conditions are presented in Section III   Section IV and V present the recommended design approach and techniques for nozzle cooling, sealing, alignment and translation

I,A, Scope (cont)

Nozzle thermal and performance design data are presented in Section IV. This data can be used to predict nozzle length and weight vs delivered performance as well as nozzle cooling requirements for various nozzle extensions attachment area ratios and overall area ratios Section IV, F, identifies the design and use limitations of the recommended radiation cooled nozzle extension concept

Section VI, identifies the supporting design analyses required to accomplish the successful design of an extendable – retractable nozzle system.

Obviously, the design of a deployable nozzle system for a specific engine was not completely covered in this program. However the material presented includes the basic data and information necessary to the design of a successful system Specific supporting data, analyses and documentation pertaining to the information presented in this volume is compiled in Volume I of this report (Tradeoff Studies, Section III, B, and Technical Analysis, Section III, C)

B   REQUIREMENT FOR USE

The most obvious application of an extendable – retractable nozzle extension is to enhance the performance of a space engine by increasing the expansion ratio of the exhaust nozzle without increasing vehicle length   A second application is to vary engine area ratio as its pressure environment changes, i e. altitude compensation   Although the latter concept was not addressed in detail since the program requirement was limited to space operating engines, much of the data presented is applicable   A need for both high expansion ratio and reduced vehicle length is required to justify the use of a movable nozzle extension, since the weight of the translation system and nozzle attachment joint would otherwise penalize system performance   The fixed geometry axially translating nozzle extension satisfied both performance and

I,A, Scope (cont)

geometry requirements provided that the movable nozzle extension maximum diameter can be accommodated within the vehicle's diametral dimensions.

The extendable – retractable technique of packaging not only minimizes vehicle interstage length and weight, but is suited to systems which must remove the nozzle extension from aerodynamic surfaces such as would occur as a spacecraft's re-entry into the earth's atmosphere The nozzle extension can be deployed, the engine fired for a desired duration and then the nozzle retracted and stowed until required for additional periods of thrusting

C. INFLUENCE OF DEPLOYABLE NOZZLE DESIGN ON TOTAL SYSTEM

Of major concern to the vehicle system's analyst is the weight of the total engine system with respect to delivered performance Of this, the nozzle extension and translation system accounts for approximately 25% of the total engine weight depending upon the specific engine design and configuration On a high pressure, gimballed, pump fed engine, the extendable nozzle system is a smaller portion of the total engine weight than on a low chamber pressure fed engine The requirement of the extendable – retractable engine nozzle design is to provide the most performance for the least engine weight Systems analysis is necessary to trade the influence of interstage weight and engine weight and area ratio for mission optimization.

II.   OPERATING CONDITIONS - DEPLOYABLE NOZZLE ENGINE SYSTEM

This section of the design guide identifies the operating conditions of the LO_2/LH_2 extendable - retractable nozzle engine system under consideration The conditions presented are for the most part specific with respect to operation, although there are areas which would require definition before a design could be finalized.   The assumed engine and system operating conditions are as follows

Propellants: LO_2/LH_2

Chamber Pressure (P_c)   300 to 800 psia

Thrust (F)   5K to 20K

Nozzle Expansion Ratio (ε):   From 50 1 to 300 1

Environment   Space (sea level fire testing is assumed necessary)

Nozzle Operation   The nozzle is deployed prior to engine firing and may be retracted following engine firing or prior to vehicle re-entry.

Nozzle Gimballing   The nozzle will not be gimballed during the process of nozzle deployment or retraction

Nozzle Cooling.   Radiation is the preferred method

Nozzle-Chamber Interface Cooling.   As required.

Supplemental Nozzle Coolant   (1)   Hot Gas

(2)   Propellants

Nozzle Extension Attachment Area Ratio   Between 100 1 and 180 1

Nozzle Weight.   Minimum

"G" Loads·   (1)   During engine operation - to be determined

(2)   Engine not operating (main stage operations only) - to be determined

Structure   It is assumed that the nozzle extension and adjacent sealing interfaces are round following initial fabrication but, because of service requirements, parts may not be round following repeated engine operation   The seal designs will be interchangeable and the ability to compensate for out-of-roundness or local discontinuity will be built into the seal or sealing interface design.

II, Operating Conditions (cont)

Temperature and pressure environment of the nozzle seal

Temperature

Sealing (prior to engine start)· To be determined
Sealing (Engine ON)
     Cooled. Turbine Exhaust· <1000°R
             Propellants·   < 700°R
     Uncooled.   <2500°R
Prior to Sealing   Ambient, vacuum and earth

Pressure

During Engine Operation. <10 psia
Prior to and Following Engine Operation   Vacuum and earth ambient
Engine Service Life   Reusable
Seal Service Life   Same as engine service life
Acceptable Seal Leakage. To be determined
Power Supply – Nozzle Deployment Actuators
Actuators   28V Electrical

III   DESIGN OBJECTIVES AND REQUIREMENTS

A   GENERAL

The extendable – retractable nozzle engine design must provide a
system for space operation that is (1) compatible with the propellants LO_2/LH_2
and their products of combustion, (2) light in weight, (3) reliable, (4) capable
of extended duration operation, and (4) capable of recycling   It must also
be remembered that additional objectives such as system reliability, simplicity,
ease of development and fabrication and minimum cost must go hand in hand with
the above

B.   OBJECTIVES AND REQUIREMENTS

The studies conducted on this program have resulted in the identi-
fication of specific design objectives and requirements as well as optimum
configurations for nozzle cooling, sealing and translation as outlined above
These are as follows.

- Upon a system or engine failure, the rocket engine and nozzle
  translation system shall be incapable of automatically retracting
  the nozzle extension to the stowed and locked position without an
  external command signal

- A single point failure of the nozzle extension deployment and
  retracting mechanism shall not prevent the nozzle from translation
  and locking

- The deployment system should have a minimum number of supporting
  mechanical devices and/or moving components for increased
  reliability

- The extreme operating environment should not cause translation,
  alignment or nozzle sealing problems

III,B, Objectives and Requirements (cont)

- Expansion of the nozzle or chamber due to heat soak from engine firing will not affect the translation system

- The mechanical power drive system should be designed for redundancy to assure nozzle translation in the case of component failure

- The nozzle extension should be of a radiation cooled design for it provides the simplest cooling method, is lightest in weight, higher in reliability, and easier to develop and fabricate than the tube bundle or transpiration cooling concepts

- The nozzle translation system should be electric motor driven Electric motors have demonstrated, (1) operational reliability in space applications, (2) best repeatability because of fewer critical parts, and (3) exhibit constant force at every position

- The nozzle extension guide and support system should be used only for the guide and support of the nozzle extension as it translates from its stowed to extended position   It should not be used to accomplish final alignment of the nozzle extension to the combustion chamber

- Metal parts which slide or roll on each other should be made of insoluble pairs and/or lubricated with a solid bonded dry lubricant to prevent cold welding in the space environment   Space lubricants are commercially available

- The nozzle translation system should incorporate the power drive mechanism, guides and support rails, and locking features into one simple mechanism for increased reliability, ease of development, and low weight

III,B, Objectives and Requirements (cont)

- The nozzle translation system should be self-supporting and should not use turbine exhaust to drive the nozzle deployment actuators   The use of this power media creates critical nozzle deployment and engine starting sequence problems and requires control systems (valves, timers and plumbing) which increase system weight and decrease reliability

- The nozzle should be designed for a minimum discontinuity at the interface between the fixed portion of the nozzle and the movable extension   The nozzle contour should be as continuous as possible, and rapid divergent or convergent steps eliminated since the steps create undesireable heat loads and possible loss in nozzle perform- ance $(I_{sp(del)})$

- In selection of the nozzle extension attachment area ratio, consideration must be given to the thermal loads at the attachment station as well as engine length reduction   If the attachment area ratio is in a high heat flux region consideration should be given to supplimental cooling of the extension attachment joint area

- The interface joint should use a gasket face seal to eliminate the problems of clearance, compression, and seal interface concentricity associated with a piston or diametral seal

- The seal should be elastomeric to provide good sealing character- istics and be located in a cool or supplimentary cooled region   Leakage rates of the specific seal design must be evaluated by testing

III,B, Objectives and Requirements (cont)

- Radiation effects on organics and polymers should be considered when choosing materials for seal designs

- Nozzle alignment should be repeatable and unaffected by mating parts concentricity, and the extreme operating temperature environment

- If a coolant source, such as turbine exhaust gas, is available at no penalty to the engine or system, it may be used to supplimentally cool the nozzle joint and extension

- Nozzle alignment technique should be repeatable and independant from the power transmission system

IV   NOZZLE DESIGN

    A.   GENERAL

        For extended steady state duration and cyclic operation, a means of cooling is required for the movable nozzle extension Several techniques of nozzle cooling were evaluated during the program studies, but the concept best satisfying the study requirements of simplicity, reliability, light weight, and ease of fabrication and development was the concept of radiation cooling This resulted in the selection of radiation cooling for the nozzle extension design shown in Figure 1   The concept shown includes two major areas of design the interface between fixed and movable portions of the nozzle extension which includes sealing, possible supplemental cooling, and alignment, and the nozzle extension itself

    B   EXTENSION ATTACHMENT JOINT DESIGN

        1   General

        The attachment joint is considered to be that area bounded by the forward end of the movable extension and the aft edge of the fixed portion of the nozzle. This is based on the fact that when the nozzle is extended the two parts overlap to provide adequate sealing and support   The nozzle and interface designs are interrelated and the influence of each must be considered in the design of the other   The major factors affecting the joint design are (1) its location, (2) the local heat loads, (3) the availability of secondary coolant, (4) sealing, and (5) nozzle alignment and support

        There is an additional factor which is not necessarily related to the previous five   This has to do with minimizing the flow discontinuities as the exhaust bases move from the fixed to the movable nozzle   It is assumed that the fixed portion extending from the combustion chamber to the attachment area is regeneratively cooled and is of a tube bundle or slot configuration

IV,B, Extension Attachment Joint Design (cont)

Nozzle thermal analysis has established that the heat load at
the point of reattachment of the main stream flow resulting from discontinuities
at the nozzle extension joint can be approximately three times that for a smooth
wall   This flow phenomena is shown in Figure 2a and discussed in Section IV, D,
2 (attachment region heating)

2   Joint Selection

As previously stated, the primary concern of the nozzle designer
is to provide the maximum performance with minimum system weight   Studies of
nozzle performance conclude that the closer to the throat that the extendable
nozzle is attached, the lighter the complete nozzle assembly

In selecting the attachment area ratio, the designer must
concern himself with the requirement that (1) the extension moves forward
around the thrust chamber and other engine components on some system of guides
and supports, (2) that the specific thermal conditions may tend to make the
attachment station move aft contrary to length considerations, and (3) that the
interface wall discontinuity between the fixed portion of the nozzle and the
movable nozzle extension be a minimum   Joint location will be the result of a
tradeoff of delivered performance (I_{sp}), nozzle weight, and the operating
thermal limitations of the nozzle material and coolant system selected

3   Joint Cooling

The attachment region will require some form of cooling
Conduction of heat to cooled parts of the fixed nozzle or the use of supplementary
film cooling is the preferred arrangement   Since the area to be cooled is
relatively small and operates at low fluxes and the cooling system can be a part
of the fixed nozzle, a variety of film cooling techniques are attractive (Figures
1 and 3)

IV,B, Extension Attachment Joint Design (cont)

The nozzle wall is discontinuous at the joint between the fixed
and extendable parts of the nozzle The magnitude of the discontinuity of the
wall will depend upon the particular design and, thus, so will the required
cooling Generally, the wall discontinuity will be such that a cavity in the
nozzle wall is present and a zone of separated flow exists within the cavity
The simplest cooling system for the cavity and attachment point is to film cool
using either propellant or gas generator effluent This type cooling system
selection will depend on the availability of a suitable coolant The three
different joint components which benefit most from supplemental cooling are the
seal, the trailing edge of the fixed nozzle, and the moving extension The inter-
face design should be integrated that the coolant is effective in each area
(Figure 1)

Nonmetallic seals have an operational temperature limit at
which they either lose sealing capability or incurr a decrease in use life
Seal cooling is effected by directing the coolant on the seal or by conduction
to adjacent surfaces which are conductively cooled

The design of the trailing edge of the fixed nozzle presents a
problem in that although it is desirable to have this tip machined to a minimum
thickness to minimize flow discontinuities the very thin sections provide poor
conductive paths If film cooling is not used, the designer must determine how
thin the tip may be to be conductively cooled and yet present a minimum flow
discontinuity This discontinuity, in turn, affects the heat flux to the nozzle
extension at the point of reattachment of the flow If film coolant is available,
it may be utilized to cool the nozzle trailing edge and by proper injection in,
around, or through the tip area (Figures 4 through 10), cool the nozzle
extension forward end

In any particular case the vehicle mission requirements and
engine design constraints need to be considered in selection of a cooling system
It may be necessary to parametrically examine several systems in order to obtain
an optimum system

IV, B, Extension Attachment Joint Design (cont)

4 Joint Sealing

The following engine operating requirements impose constraints on the selection and design of a joint seal   (1) joint sealing is not required during nozzle translation, (2) the nozzle extension and adjacent sealing interfaces may not round following repeated 'engine operation, and (3) positive sealing must be accomplished under conditions of engine operation

Several techniques of joint sealing were investigated and the technique which most satisfied the design constraints found to be the elastomeric face seal   This concept is shown in Figure 1   The seal is located in an area well removed from the heat input to the extension, and seals not only from the mouting ring to the flange brazed to the tube bundle but also seals the extension to the mounting ring as well   A positive seal is assured by serrations machined in the surfaces of all parts that contact the seal   The amount of gasket "crush" is controlled between extension and mount ring by interlocking lips   The maximum operating temperature for an elastomeric seal is approximately 700°F

Seal replacement is accomplished by fully retracting the extension and then unbolting the extension from the mounting ring   The seal is then cut and removed   The new seal is stretched over the fixed portion of the nozzle, inserted in the flange, and the bolts replaced   On small diameters, it may be necessary to split the seal on the bias and to reseal on assembly with a silicone rubber adhesive

This sealing technique is both positive and insensitive to machining tolerances   It does require that the translation system lock or hold the seal in compression during extend and engine firing modes

Radial and face seal inflatable elastomeric and metallic concepts are recommended as alternates if engine operating conditions and heat loads are restrictive to the proposed concept

IV, B, Extension Attachment Joint Design (cont)

The inflatable sealing techniques (Figures 11 and 12) were ruled out as a primary concept If turbine exhaust gas, assuming low temperature and low pressure products are available is used as the pressurant, only the short period of time between turbo pump start and engine fire would only be available to accomplish successful interface sealing This might not be a problem due to the time needed to heat and expand the seal In addition, the metal seal would be unable to follow irregular surfaces on the interface and hence would not be leak tight The inflatable concepts, whether they use turbine exhaust or some other pressurant, would require plumbing and controls for the pressurant supply

5   Nozzle Alignment

Nozzle alignment is concerned with the linear and angular mismatch of a theoretical centerline defined by the nozzle throat and injector end of the thrust chamber and a similar centerline through centroids of the throat and the nozzle exit plane

Misalignment tolerances are usually held very close, perhaps on the order of 0 25° or less This is because the engine is usually mounted in the vehicle using the thrust chamber centerline as the mounting guide, generally placing it in parallel with the vehicle and thrust centerline For single nozzle vehicles these centerlines are coincident It can readily be seen that, for a fixed, single nozzle application, any misalignment built into the nozzle now represents a moment arm of the resultant thrust vector about the vehicle center of gravity Similarly, over-tolerance thrust misalignment in a multi-engined application might result in vehicle turning moments or thrust losses which are undesirable

IV, B, Extension Attachment Joint Design (cont)

If the engine is not fixed, but gimballed, the small amounts of misalignment present in most engines can be corrected for by a slight movement of the gimbal actuators This action in turn reduces total gimbal movement in that direction by a like amount

For an extendable nozzle, it can be assumed that the misalignment present in the fixed portion of the engine is small and can be held to conventional tolerances by conventional methods This is not true of the extendable exit cone or moving portion, however This section, supported by some sort of guides and moved in to position by an actuation system, must be designed to reduce misalignment between it and the fixed portion of the nozzle It is true that if the extendable nozzle engine is gimballed, this misalignment can be corrected by slight gimbal movement It must be remembered, however, that the misalignment of the extendable nozzle occurs within the divergent portion of the nozzle iteself, at the joint attach line and probably at a fairly high area ratio A severe misalignment at this point can result in a loss of performance

In any case, it is important to keep misalignment between fixed and moving portions of an extendable nozzle to a minimum, probably meeting a total tolerance for the fixed and movable sections on the order of that allowed for conventional nozzles

The considerations for nozzle extension alignment design are (1) alignment should be repeatable and little affected by initial or subsequent lack of mating part concentricity, (2) accomplished so that it is unaffected by the extreme temperature differentials expected from both the space environment and engine operation, and (3) independant from other systems for system simplicity and reliability The recommended technique satisfying these requirements is shown in Figure 1

IV,B, Extension Attachment Joint Design (cont)

Alignment is accomplished by the use of springs located in the two flanges brazed to the tube bundle fixed portion of the nozzle The springs push radially outward with a uniform force which is sufficient to keep the extension centered about the tube bundle under normal engine loads The force is not so great, however, as to create frictional forces which might tend to prevent extension or retraction To help reduce friction, the use of a dry powder lubricant such as Microseal 200-1 is recommended on the inner diameter of the extension in the areas of spring contact and possibly on the springs

This system aligns the extension to the tube bundle That is not to say that the tube bundle flanges are perfectly circular or concentric, but assuming that they are turned to specified tolerances and subjected to uniform thermal loads, the deviation from machining dimension tolerances should be minimal The springs will insure that the centerline of the fixed nozzle exit plane and that of the extension coincide without alignment being required from the translation system other than that necessary to guide the extension until it engages the springs Angular offset of the two centerlines is prevented by using the compression gasket surfaces for alignment This requires that both flanges be normal to the nozzle axis

The nozzle guide and support system is designed "loose" enough so as to allow the interfacing springs surfaces to accomplish final alignment at the end of nozzle travel The metal spring is designed to give slightly during seating and alignment so that the lack of exact concentricity of parts will not be a problem Finally, even though both the fixed and moving parts should be heated or cooled together in an ideal situation, the cylindrical springs have the ability to compensate for differential temperatures between the mating surfaces, allowing the parts to seat at slightly different longitudinal and radial position

IV, B, Extension Attachment Joint Design (cont)

A section of the spring is also shown in Figure 1 It is fabricated from a flat strip, the serations or slots cut in it, the curvature imparted to the slit section and then the final bend made as shown The strip can now be bent around and placed in the groove of the tube bundle flange as shown Pins or screws can be used to secure the spring ends

6   Materials Selection

Selection of materials for nozzle construction is dictated by the strength requirements and the operational environment as well as the usual criteria for materials used in a liquid rocket engine nozzle These are compatibility with the propellant combustion gas environment, fabrication and quality control of the hardware, and the capability of surviving cyclic operation

The designer must satisfy himself that the materials selected for use in the extension are compatible with the exhaust products of LO_2/LH_2 If they are not, he must determine the resulting rates of corrosion or grain boundary layer contamination and see if the anticipated mission duration can still be met without failure He must also consider the cyclic effects of heating and cooling on the material and insure if the cyclic life required for the extension is met or exceeded

7   Coatings

If the combustion products are corrosive to the selected material, the extension can be protected by the application of one of several commercially available coatings that either eliminate or substantially delay the onset of corrosion These coatings are generally silicides or aluminides and as pointed out in the thermal analysis, enhance the emissivity characteristics of the radiation cooled nozzle extension Although coating types and techniques were examined, detailed investigation was considered unnecessary due to general availability of data

IV,B, Extension Attachment Joint Design (cont)

8   Loads

Once steady state temperatures throughout the extension have
been determined for the selected extension, type and material, the loads acting
upon the extension must then be determined to see if the stress levels of the
material have been exceeded (see Section VI, supporting design analysis)

Generally, the loads acting upon the extension that must be
considered in any analysis are

a   Hoop loads due to internal pressure

b   Axial (thrust) loads due to internal pressure

c   Axial loads on the vehicle due to thrust

d   Lateral loads due to maneuvering or gimballing

e   Thermal loads due to expansion and restraint

These loads must be summed to determine the total load imposed
on the extension This summation represents the axial, shear, and bending loads
which must be carried through the attachment end of the nozzle extension

Once the loads on the extension have been determined, the
designer, working with an imposed factor of safety, must satisfy himself that the
initial design is adequate to handle the imposed loads and temperatures   If not,
the design is modified until thermal and force loads can be safely handled   As
an alternative, secondary cooling (discussed in Sections IV, B, 2, and D, 3,
(a)) may be used to lower equilibrium temperatures

C   SUGGESTED EXTENSION DESIGN APPROACH

The following represents a recommended procedure for design of a
nozzle extension

IV,C, Suggested Extension Design Approach (cont) `

    1   Gather input data

        a   Operating chamber pressure (P_c) - from vehicle systems analyst

        b   Throat diameter (D_t) - from vehicle systems analyst

        c   Propellant properties - from vehicle systems analyst

        d   Mixture ratio and mass flow $(\dot{w}_o/\dot{w}_f)$ - from vehicle systems analyst

        e   Overall expansion ratio (ε) - from performance analysis

        f   Inner contour (L/L_{min}) - from performance analysis

        g   Number of firing cycles - from vehicles systems analyst

        h   Longest firing duration - from vehicles systems analyst

        i   Total firing duration - from vehicles systems analyst

        j   Nozzle environment - from vehicles systems analyst

        k   Thrust chamber diameter (inches) - from performance analysis

        l   Overall chamber length (inches) - from performance analysis

        m   Nozzle length (inches) - from performance analysis

    2   Determine the nozzle wall heat flux for a continuous wall as a function of chamber pressure and thrust   Ref   Nozzle Thermal Design, Section D, 1

    3   Establish the nozzle attachment point   As previously stated, the nozzle designer must provide maximum performance (I_{sp}) at the selected operating chamber pressure for minimum system weight   The use of Section IV, E (Nozzle Performance Analysis) of this report will assist in defining this selection   The nozzle performance analysis shows that this is accomplished by choosing the attachment area ratio to be as small as possible while still operating within the thermal limits of the material selected for the nozzle extension

IV,C, Suggested Extension Design Approach (cont)

4   Determine the new local heat transfer coefficient at the
attachment point   The thermal analysis states, the rule of thunb in determining
the heat load resulting from flow interruption by the interface discontinuity,
is that the heat transfer coefficient is that of a smooth wall multiplied by a
factor of three

5   Select extension material considering strength and corrosion
attack of exhaust products at elevated temperatures   A columbium alloy such
as C-103 is recommended   The C-103 material used on the Apollo SPS nozzle
extension operates at temperatures in excess of 2000°F

6   Make initial extension design   Using columbium, experience dictates
0 030 to 0 040 in wall thickness at the attachment area, which may be thinned
toward the exit

7   Conduct heat transfer analysis to determine equilibrium
temperatures through nozzle extension and attachment interface   The attachment
interface contains the seal   Maximum steady state operating temperature for the
proposed seal material is approximately 600 to 700°F

8   Conduct thermal stress analysis to determine predicted stress
levels throughout nozzle as a function of thermal expansion, internal pressures,
and anticipated accelerations

9   If using a preselected margin of safety, acceptable stress
levels at operating temperatures are exceeded in any region of the extension
(usually in the attachment region), repeat Steps 3 through 8 until a satisfactory
design is obtained or consider the use of supplimentary cooling if the low area
ratio of attachment is still required to meet performance and weight goals

IV,C, Suggested Extension Design Approach (cont)

10   If the corrosive effects of the exhaust products on the
extension material at elevated temperatures are considered excessive based on
the firing durations expected, select either a silicide (preferred) or aluminide
coating to be applied to the extension ID   (This provides added insurance for
any extension design to be fired more than once)

11   Determine if fatigue presents a problem for either the coating
or base material life as a function of the required number of firing cycles
Preventive maintenance (inspection and recoating may be necessary if the number
of cycles is high

12   Electron beam weldments are recommended for fabrication of
radiation cooled extensions

D   NOZZLE THERMAL DESIGN

1   Smooth Wall Heat Transfer

The thermal design of an extendable nozzle requires that the
heat flux to nozzle wall be established for both the smooth wall portions and
at the discontinuity caused by the joint for attachment of the extendable portion
to the fixed part of the nozzle   The heat flux to the smooth wall portions
of the nozzle can be established with good reliability using existing film
coefficient correlations   The accuracy of these methods has been verified in
the course of development of many liquid propellant rocket engines

The heat flux in the attachment region must be estimated using
the limited amount of experimental data which exists for supersonic flow over
cavities   These data have been references to the smooth wall heat transfer as
a means of correlation   Thus, the smooth wall heat transfer coefficient also is
used in establishing the heat transfer to the joint or cavity flow regions of the
extendable nozzle

IV,D, Nozzle Thermal Design (cont.)

Heat transfer from the hot exhaust gas to the nozzle wall occurs mainly by convection The nozzle wall usually is at some temperature below the mainstream gas temperature, which results in a temperature differential across the nozzle wall boundary layer This temperature gradient produces a transfer of heat from the hot gas to the nozzle wall In addition, the high temperature exhaust gas will radiate heat to the nozzle wall Gas radiation is not as well understood as simple convection, but it is known to be a second-order effect for LO_2/LH_2 propellants and usually may be neglected in design calculations

The convective heat transfer rate per unit area, Q_c, from the combustion gases to the nozzle wall is predicted using the familiar Newton's Law equation

$$Q_c = h_g (T_r - T_{wg})$$

In this equation, h_g is the hot gas film coefficient and T_r is the gas recovery temperature The chamber wall temperature, T_{wg}, will depend on the method of cooling the wall, the wall thermal properties, and other factors

The recovery temperature is calculated using Equation 2 which is applicable only to the turbulent flow in the exhaust region of thrust chambers

$$T_r = \eta^2 [T_s + Pr_s^{1/3} (T_Q - T_s)]$$

$$\eta = \frac{c^*\ \text{chamber}}{c^*\ \text{theo}}$$

(Eq 2)

The combustion efficiency, also known as the c' efficiency, is calculated as the square root of the ratio of engine c^* to theoretical c^* The stagnation temperature or flame temperature, T_0, is the theoretical combustion temperature of propellants at the combustion chamber pressure and injector mixture ratio chosen for engine operation T_0 is obtained from thermochemical calculations, which include the effect of pressure and temperature on the equilibrium chemical

IV,D, Nozzle Thermal Design (cont)

composition of the gases   The gas stream static temperature, T_s, usually is
calculated assuming isentropic gas flow with shifting chemical equilibrium
The Prandtl number (Pr) is relatively insensitive to pressure and temperature
and may be evaluated at local conditions

The hot gas film coefficient (h_g) is calculated for use in the
smooth contour region of extendable nozzles by use of the simplified form
Bartz equation (Eq 3) with a modification to account for two-dimensional gas
flow effects in the expansion region of the nozzle

$$ h_g = \frac{0\ 026}{D_c^{0\ 2}} \left[\frac{\mu^{0\ 2} c_p}{Pr^{0\ 6}} \right]_f (\rho v)^{0\ 8} \left(\frac{T_{2-D}}{T_f} \right)^{0\ 8} \qquad (Eq\ 3) $$

and

$$ T_f = 0\ 5\ (T_r + T_w) $$

In Equation 3, the two-dimensional mass velocity, $(\rho v)_{2-D}$, has been substituted
for the one-dimensional mass velocity employed by Bartz   This modification
results in h_g prediction and convective heat flux that is as much as 30% higher
than predictions using the one-dimensional Bartz equation   The temperature
ratio accounts for the gas density gradient in the thermal boundary layer   The
improved correlation obtained by inclusion of the two-dimensional mass velocity
term in Equation 3 has been well substantiated by rocket engine test data

The Bartz film coefficient correlation has been used to prepare
a parametric plot of the smooth wall film coefficient for the range of
parameters of interest in design   Range of parameters for which the parametric
data have been prepared are   propellants LO_2/LH_2, MR - 6 0, chamber pressure 200
to 800 psia, area ratio 50 to 300, and thrust 5K to 20K lb

IV,D, Nozzle Thermal Design (cont.)

The film coefficient is obtained from Figure 13 using the values of area ratio, chamber pressure, and thrust for a particular case   The factor $(F/P_c)^{0.1}$, which appears in the ordinate, is a scale factor to account for the variation of nozzle size   The correlation has been found to be most accurate when the gas properties are evaluated at the film temperature, $T_f = (T_r + T_w)/2$, which is defined as the arithmetic mean temperature between the free-stream recovery temperature, T_t, and the wall temperature, T_w In order to accomplish this correction, the film coefficient for bulk conditions, obtained from Figure 13, is multiplied by the ratio of the DB factor for the film temperature to the DB factor for bulk conditions   The DB factor is defined by the following equation

$$DB = 0.026 \frac{C_p \, \mu^{0.2}}{Pr^{0.6}} (\frac{4}{\pi})^{0.8}$$

which contains the fluid property terms from Equation 3 that are a function of temperature   The recovery temperature is calculated using Equation 2 with T_s determined from Figures 14 and 15   The DB factors corresponding to film and bulk temperatures are obtained from Figure 16

2   Attachment Region Heating

The joint between the fixed and extendable portions of the nozzle results in a discontinuity in the nozzle wall contour   The discontinuity will cause some disturbance of the boundary layer flow and if the size of the discontinuity is much larger than the boundary layer thickness the main flow will be affected also   Small discontinuities which affect only the boundary layer will have a relatively small effect on the heat transfer, but will result in increased heat flux over that for a smooth wall   Large discontinuities will cause boundary layer flow separation at the upstream edge of the discontinuity followed by reattachment of the flow near the downstream edge (Figure 2)   A region of separated flow will exist within the cavity of the wall discontinuity The heat transfer is reduced in the separated flow region, but at the point of

IV,D, Nozzle Thermal Design (cont)

flow reattachment the heat transfer is increased by a factor from 1 to 3 times
the flux for a smooth wall   The extendable nozzle wall discontinuity is most
nearly like the open cavity shown on Figures 2a and 17

At the present time, insufficient data exist to accurately
define the maximum heat transfer coefficient which will occur within a cavity
of the extendable nozzle type for an arbitrary configuration and Mach number
However, it is conservatively estimated to be 3 0 times the heat transfer
coefficient for a smooth wall (see Figure 18)

The heat flux within the separated flow region is also of
interest, since some cooling may be required in the joint region of the cavity
as well as at the point of maximum heat flux   Generally, the heat transfer
coefficient within the separated flow region of the cavity is less than the heat
transfer for a smooth surface   A value for the heat transfer coefficient between
0 6 and 0 8 that of the smooth wall value is reported in References 1 and 2
Here again, because of inadequate data, it is necessary to choose the higher value
for design purposes

The increased heat flux at the extendable nozzle joint over
that for a smooth wall affects the selection of the area ratio at which a
radiation cooled extension can be attached   A radiation cooled nozzle extension
is limited, usually, by the temperature and heat flux at the attachment point
Therefore, with a cavity at the attachment point, the limiting attachment area
ratio increases to a point at which the smooth wall heat flux is 1/3 the
maximum for radiation cooling   This effect can be reduced or eliminated through
the use of supplemental film cooling to reduce the maximum heat flux

3   Radiation Equilibrium Wall Temperature

The most desirable nozzle extension cooling system is the radiation
cooling concept   This technique is completely passive and results in a mechanically

IV,D, Nozzle Thermal Design (cont)

simple system   However, materials selection becomes very important since the
nozzle is required to operate at high temperature in a corrosive atmosphere
A list of several high temperature metals is shown in Table I

The equilibrium wall temperature of a radiation cooled nozzle
wall is established by equilibration of the heat flux to the nozzle wall due to
convection and the heat flux from the wall due to radiation   In the analysis of
this process, the temperature drop across the nozzle wall can be ignored because
of the relatively low heat flux and the high conductivity of the metal wall
The axial conduction along the nozzle wall is also neglected because of the small
temperature gradient along the wall

The nozzle wall temperature is calculated by a heat balance on
the wall   The radiant heat flux from a unit area element of the nozzle wall is
given by

$$q_{rad} = \Sigma_{\alpha\mu i} \; \xi_{wi} \sigma \; (T_w^4 - T_i^4) \qquad\qquad (Eq \; 5)$$

where

F = Surface view factor

σ = 3.306 x 10^{-5} Btu/sec-in ^{2}-°R Stefan Boltzman constant

T_w = Wall temperature

T_i = Temperature of surface to which energy is being radiated

It can be shown that energy radiated between any element of the
nozzle and any other element may be neglected compared to the energy radiated to
space   Simplification of the above expression and assuming a view factor of
unity for radiation from the outer surface yields an expression for the energy
radiation to space

$$q_{rad} = (F_o + 1) \sigma \; \epsilon_w \; T_w^4 \qquad\qquad (Eq \; 6)$$

where F_o = View factor from inner surface to space

IV, D, Nozzle Thermal Design (cont)

The view factor from the inner surface to space is a function of the nozzle geometry and is shown plotted in Figure 19 as a function of the nozzle area ratio for three overall nozzle area ratios

At equilibrium, the radiant heat flux is equal to the convective heat flux to the nozzle wall.

$$q_{conv} = h_g (T_t - T_w) = q_{rad} = (F_o + 1) \sigma \epsilon_w T_w^4 \qquad (Eq\ 7)$$

or

$$\frac{T_r - T_w}{T_w} = \frac{(F_o + 1) T \epsilon_w T_w^4}{h_g} \qquad (Eq\ 8)$$

The equilibrium wall temperature, T_w, is shown plotted in Figure 20 as a function of the right-hand side of Equation 8 and for three values of the recovery temperature.

a.   Film Cooling

(1) General

Film cooling is a form of mass transfer cooling in which the coolant is introduced on the surface to be cooled through discrete slots or holes Either a gas or a liquid may be used as a film coolant The coolant is injected in such a manner that a protective layer is formed between the surface to be cooled and the hot gas stream. As the film coolant flows along the wall, it is both heated by the hot gas stream and dispersed by turbulent mixing with the high velocity nozzle flow The mixing process continues until all of the film coolant is dispersed homogeneously in the high temperature nozzle gas Additional coolant must be supplied at intervals in order to provide continuous cooling, if required Because of the relatively large mass of coolant that is required, rocket systems suffer a penalty in specific impulse when film cooling is used as a primary cooling system Therefore, film cooling usually is employed as a supplement to some other primary means of cooling such as a regenerative or radiation cooled system

IV, D, Nozzle Thermal Design (cont)

The primary applications of film cooling for the extendable nozzle are as supplemental cooling schemes for the joint region and possibly a short section of the extendable portion of the nozzle

Although either a gas or a liquid film coolant could be used, the use of a liquid has a number of difficulties which reduce its attractiveness relative to gaseous coolants. These include. (1) coolant injection orifices must be very small in order to obtain uniform distribution of the coolant over the surfaces to be cooled, (2) the performance loss with liquid film cooling in the supersonic nozzle will be significantly greater than with gaseous film cooling, and (3) analytical methods for predicting liquid film cooling effectiveness in the supersonic nozzle are nonexistent. These problems are encountered to a lesser degree when a gaseous film coolant is employed

(2) Analysis

Early subsonic film cooling analyses were generally based on the model of Hatch and Papell (Ref 3) and Papell (Ref 4) In order to apply this model to a rocket nozzle geometry, it was necessary to modify the model slightly to account for variations in the nozzle gas mass flow

A limited amount of experimental data for film cooling in a supersonic air stream was obtained from air turbine nozzle experiments conducted at the General Electric Co (Ref 5 and 6) Recently, Goldstein, et al , experimentally investigated film cooling injection from a rearward facing step into a supersonic air stream (Ref 7 and 8) Zakkay, et al (Ref 9), has conducted experiments similar to those of Goldstein but using supersonic coolant injection velocities. The air film cooling data of Reference 7 were correlated using the following equation.

$$\eta = \frac{T_{wa} - T_r}{T_c - T_r} = (\frac{15\ 5}{\xi})^{2.5}, \text{ for } 15\ 5 < \xi < 39 \qquad (\text{Eq } 10)$$

IV, D, Nozzle Thermal Design (cont)

where $\xi = (\frac{x}{h}) (\frac{T_o}{T_c}) (\frac{1}{M})^{0\ 27}$ 　　　　　　　　　　　　(Eq　11)

x 　= Film cooled length

h 　= Coolant slot height

T_o 　= Mainstream gas stagnation temperature

T_c 　= Coolant supply temperature

M 　= Ratio of coolant to mainstream mass velocity

T_{wa} = Adiabatic wall temperature

and

$$\eta = 1\ 0 \text{ for } \xi \leq 15\ 5$$

The ratio of the coolant injection velocity to mainstream velocity does not appear explicitly in Equation 10 but is contained in the parameter M and, in contrast to the subsonic data, Equation 10 predicts a continuous increase in effectiveness with increased coolant injection velocity if the density is held fixed   This result probably is due to the fact that test data only exist for velocity ratios less than unity and, thus, the behavior at higher values is unknown   A similar trend has been noted in subsonic velocity, since this variation had not been included in the model   More effectiveness is observed for velocity ratios slightly greater than one

No data exist which show the effect of injection angle on the film cooling effectiveness for supersonic film cooling, however, some reduction in effectiveness is to be expected with increasing injection angle in a manner similar to the subsonic case

Although the existing correlations for supersonic film cooling data do not apply to a situation as complex as the flow at the joint between the fixed and extendable portions of the nozzle, it is possible to draw certain conclusions with respect to the design of a film cooling system   (1) the

IV, D, Nozzle Thermal Design (cont.)

static pressure of the coolant at the point of injection should match or be slightly greater than the static pressure of the main nozzle flow at the injection point (this will assure minimum disturbance of main flow which will reduce the rate of mixing between the two streams and will result in minimum performance degradation due to disturbance of the main nozzle flow), (2) the coolant should be injected at the highest possible velocity, up to a velocity equal to that of the main flow, consistent with matching of static pressures, and (3) the coolant should be injected in a direction as nearly parallel to the mainstream as possible in order to reduce interaction losses

The correlation given by Equations 10 and 11 can be used to estimate the film cooling effectiveness if an effective slot height, h, is used, i.e , the equivalent annular slot height for the coolant exit. The predicted effectiveness parameter defines the local adiabatic wall recovery temperature, T_{wa}, which should be used in Newton's cooling law, i.e.,

$$q = h \ (T_{wa} - T_w) \qquad\qquad (Eq \quad 12)$$

where h is the convective film coefficient without film cooling   The heat flux, q, which is predicted in this manner, should be regarded as an optimistic estimate since the specific nature of the coolant injection geometry is not considered due to insufficient data.

b.   Prediction of Nozzle Heat Flux - Film Cooled

The methods which have been discussed for prediction of smooth wall convective film coefficient, separation - reattachment region heating, and film coolant effects on the heat transfer must be combined in order to obtain an estimate for the expected heat flux in the attachment region and the nozzle extension of the extendable nozzle. The smooth wall convective film coefficient

IV, D, Nozzle Thermal Design (cont)

is the basis for the method   The peak heat transfer coefficient at the point of
flow reattachment is obtained as an amplification to the smooth wall value
Because of limited data, a conservative estimate for the amplification factor
should be used. A value equal to 3.0 is recommended

              The effect of film cooling on the nozzle wall heat flux is
predicted by means of the film cooling effectiveness parameter, , which is used
to determine the adiabatic wall temperature. The effectiveness parameter is estab-
lished from existing correlations and is a function of length from the coolant
injection point. At each axial station, the local adiabatic wall temperature is
established and, when combined with the estimate for the convective film coeffi-
cient, can be used to estimate the heat flux using Newton's cooling law

$$q = h \ (3.0) \ (T_{wa} - T_w)$$

where h = Smooth wall convective film coefficient

              3.0 = Amplification factor for reattachment point

              T_{wa} = Adiabatic wall temperature

              T_w = Cooled wall temperature

IV, Nozzle Design (cont.)

E. NOZZLE PERFORMANCE ANALYSIS

1. General

The performance analysis presents the data necessary to optimize a LO_2/LH_2 rocket engine extendable - retractable radiation/film cooled nozzle extension for space applications.

Nozzle optimization requires that the relationship between nozzle weight, length, delivered specific impulse, attachment area ratio, and exit area ratio be known   The program studies evaluated and identified these relationships They are presented in this section of the report as parametric design data intended for use by the design engineer during the preliminary design phase of a LO_2/LH_2 space engine

The data presented are in the form of delivered specific impulse (Figures 21 through 26) and nozzle weight (Figures 27 through 30) as a function of overall area ratio. These data are also presented in the form of tradeoff ratio as a function of overall area ratio (Figures 31 through 36), tradeoff ratio is defined as $\Delta W/\Delta I_{sp}$, where W is nozzle weight. The parametric "tradeoff ratio" is a convenient link between specific vehicle mission characteristics and optimum engine design   In this form, $\Delta W/\Delta I_{sp}$ can be used to determine an optimum nozzle length once a mission analysis has been conducted to define tradeoff ratio

The absolute magnitudes of the specific impulse and weight values presented in this study are, of course, subject to the state assumptions (Section III,E,2). A complete summary of delivered performance values may be found in Tables II and III. In addition, these tables include the performance losses associated with each configuration considered   The specific impulse for a given engine system which deviates from the assumed system may then be calculated by modifying the various losses as needed.

IV, E, Nozzle Performance Analysis (cont)

The nozzle weights, as presented, may also be modified to reflect structural characteristics which are different from those assumed in the preparation of these data   For this purpose, nozzle surface areas as a function of distance from the throat are included in Table IV.

The primary influences on both nozzle performance and weight are due to nozzle overall area ratio and length   Nozzle performance increases with length and overall area ratio, however, at very high area ratios, a unit increase in specific impulse with area ratio is accomplished by a large increase in nozzle weight   Thus, there is an optimum length and area ratio beyond which the increase in weight more than offsets the small increase in nozzle performance

In addition to the primary nozzle design parameters of length and area ratio, several other parameters also impact the nozzle optimization   The attachment area ratio has a small effect on delivered specific impulse but a significant effect on nozzle weight   Considering only nozzle weight and performance effects, it is desirable to have a small attachment area ratio due to the weight savings associated with the low weight per unit area of the extension

2   Data Base

In order to examine the effects of incorporating an extendable nozzle extension into the design of an otherwise conventional rocket engine, the analysis conducted defining the above parametric relationships considered different overall nozzle expansion ratios and attachment ratios (expansion ratio at extendable nozzle interface to fixed nozzle) for a typical LO_2/LH_2 engine having the following range of operating parameters.

IV, E, Nozzle Performance Analysis (cont.)

P_c = 300 psia to 800 psia

F = 5K to 20K

ϵ = 50·1 to 300:1

Minimum attachment ϵ = 80·1

Range of attachment ϵ_1 = 100:1, 140·1 and 180.1

Two thrust chamber designs corresponding to
F/P_c ratios of 10 and 20

To accomplish this task, a midpoint or base case design was formu-
lated This design is shown in Figure 37. The characteristics of operation and the
basic values of weight and performance for the design were identified as necessary
so they could be used throughout the operating range of interest The operating
characteristics for the midpoint design were as follows·

(1) Gas generator cycle

(2) GO_2/GH_2 propellants at the injector

(3) Injector mixture ratio = 6 27

(4) Nozzle is regeneratively cooled to the extension
attachment point

(5) Turbine exhaust gas used for nozzle coolant·

MR = 1
$\dot{w}$ = 0 311
T = 860°R

The secondary gas coolant properties and engine operating conditions
are summarized in Table V.

Nozzle weights were calculated based on nozzle surface areas and
estimated weights per unit area. Two different nozzle cooling modes were considered
in calculating both nozzle performance and weight. The thrust chamber from the
injector to the attachment point was assumed to be regeneratively cooled and weigh
0.0204 lb/in.^{2}. The retractable nozzle extension was assumed to be cooled using

IV, E, Nozzle Performance Analysis (cont)

turbine exhaust gases by radiation/film cooling   The estimate of weight for the
radiation cooled section was 0 0096 lb/in.^{2} In the case of radiation/film cooling,
the turbine exhaust gases were assumed to be injected into the main flow at the
attachment point

3   Determination of Optimum Nozzle

    a   General

        The tradeoff ratio curves are intended for use in nozzle
optimization   To aid in understanding how these curves and all other data included
may be used in designing an optimum rocket nozzle, a few sample techniques are
presented

    b   Determination of Optimum Nozzle Curves

        To determine absolute nozzle lengths, the tradeoff ratio versus
area curve (Figures 31 through 36) can be plotted as a tradeoff ratio versus length
curve with lines of constant overall area ratio. These relationships are depicted
in Figure 38 for the example case of P_c = 1000 psia and throat radius equal to
1.28 in. The lengths were determined by multiplying the length ratio value for a
particular area ratio from Table IV by the value for throat radius. A plot of
delivered specific impulse versus length was constructed for constant overall area
ratio from the delivered specific impulse curves of Figures 21 through 26   This
curve is shown in Figure 39   Figures 38 and 29 were combined to form the plot of
area ratio versus length of Figure 40   Lines of constant tradeoff ratio ($\Delta W/\Delta I_{sp}$)
and lines of constant performance (I_{sp}) are shown on this plot   This curve is then
used to determine the area ratio and length of the optimum nozzle for a given system
tradeoff ratio. It should be pointed out that the delivered specific impulse data
show that, in general, increasing the nozzle length beyond approximately one and one

IV, E, Nozzle Performance Analysis (cont.)

half times the Rao minimum length would not benefit overall vehicle performance
That is, the small increase in performance with increased nozzle length would be
more than offset by the increased nozzle weight.

    c.   Sample Use Problem

        Following the completion of the vehicle systems analyses, the
engine designer will receive from the systems analyst engine design information
pertinent to the vehicle's performance requirements. For a sample problem, the
assumption will be made that the vehicle performance requirements dictate the follow-
ing engine design parameters·

$$\text{Chamber pressure } (P_c) = 1000 \text{ psia}$$
$$\text{Tradeoff ratio } (\Delta W/\Delta I_{sp}) = 4$$
$$\text{Nozzle length (max)} = 55 \text{ in} \quad \text{(packaging considerations)}$$
$$\text{Throat radius } (R_t) = 1\ 28 \text{ in}$$

        Knowing the above conditions of engine operation, the engine
designer, through the procedure as outlined above, establishes the curves as dis-
played in Figures 38, 39, and 40. Figure 40, being required to establish nozzle
expansion ratio, delivered I_{sp}, nozzle length in inches, and length ratio L/L_{min},
is the end objective.

        This curve (Figure 40) in conjunction with use of Figure 29
is all that is required to optimize the nozzle configuration, satisfying the vehicle
design requirements of the nozzle

        Knowing tradeoff ratio $(\Delta W/\Delta I_{sp})$, the designer establishes,
through the use of Figure 40, the following engine design parameters

IV, E, Nozzle Performance Analysis (cont.)

Delivered performance (I_{sp}) = 456 sec

Expansion ratio (ϵ) = 214

Nozzle length = 51 2 in

L/L_M (Rao contour length ratio) = 1 062

Knowing that the expansion ratio (ϵ) is 214 and that the contour length ratio (L/L_M) = 1 062, the engine designer can establish, through the use of Figure 29, the nozzle extension attachment area ratio and weight They are as follows·

Nozzle attachment area ratio (ϵ_1) = 100

Nozzle weight = 53 lb

The nozzle attachment area ratio can be given to the thermal analyst to establish if the heat loads at the attachment interface exceed the nozzle material limits The nozzle designer can use the estimated nozzle weight to design the translation system

IV, Nozzle Design (cont.)

F.   LIMITATION OF RADIATION COOLING CONCEPT

Radiation cooling, as with all cooling concepts, has inherent design
and use problems. They are materials and "view factor".

The maximum heat flux for which radiation cooling can be used is deter-
mined by the temperature limit of the wall material   The upper design and use limit
for radiation materials currently in use is about 2500°F   Columbium (C-103), one
of the suggested materials for use, is subject to corrosion attack by the water
vapors present in the products of combustion of LO_2/LH_2 rocket engines   However,
the rate of attack is small ($\sim$60 Mg/cm^2/hr) and can be delayed by coatings as were
used on the Apollo skirt. The problem associated with coatings used in protecting
radiation extensions is that the coating may be subject to flaking following thermal
cycling. A thousand cycle capability is considered a possibility, but required
cyclic use life must be verified by test. Other materials, based upon their use
history and well-known physical and mechanical properties, considered as possible
candidates for use in the extension design are tantalum and titanium.

The radiation concept is restricted if adjacent structures prevent
radiation of the energy to space (view factor) or if the nozzles must be clustered
together so that a significant amount of inter-engine heat flux occurs and local
hot spots result. This problem restricts use of the surrounding environment to
materials and components that are not temperature sensitive or operationally limited
by the increased temperature environment   A thermal analysis and component evalua-
tion as to temperature sensitivity is required to verify use. In cases where radia-
tion cooling appears marginal because of high heat flux, it is possible to reduce
the maximum heat flux to tolerable limits by supplementally film cooling the nozzle
extension.

V   TRANSLATION SYSTEM DESIGN

A.   GENERAL

The tradeoff studies have identified the optimum translation system
as that system which incorporates into one simple design for simplicity, reliability,
and light weight, the feature of nozzle power drive, guide, support, power trans-
mission, and locking   A system that satisfies these requirements is shown in
Figures 41 and 42   The power transmission system incorporates the features of
nozzle guide, support, and locking.

The proposed concept includes two major areas of design   selection of
a power drive system (actuator) and design of a power transmission system for nozzle
deployment and locking.

B.   DESIGN CONSIDERATIONS

1   Power Drive System

The design or selection of an actuator is, at best, a tradeoff
among interrelated factors which include (1) power requirements and source,
(2) speed, (3) operating characteristics and their repeatability under any load con-
ditions, (4) environment, (5) reversability, (6) length of stroke desired, and
(7) limitation of envelope size and weight

Based upon the evaluation of hydraulic and pneumatic cylinders and
torque motors, bellows and diaphragms, and electrical motor drives, the electric
motor drive concept was considered best to satisfy the design requirements of sim-
plicity, historical background, weight, reliability, ease of development, a minimum
of environmental and system design problems, and to require a minimum of supporting
systems such as valves, lines and controls

V, B, Design Considerations (cont.)

2. Power Transmission System

The technique of incorporating the features of nozzle translation, locking, and guide and supporting into one simple design has not only provided system simplicity and a reduction in weight, but has increased reliability by the reduction in numbers of components and provided for ease of design, fabrication, and development

The proposed system satisfies the nozzle guide and support design requirements in that the system provides guide and support to the nozzle extension at any point in travel from its retracted to extended position and holds the extension in its proper relation to the fixed portion of the nozzle It must be remembered that this system does not provide for nozzle final alignment with respect to engine centerline Final alignment has been provided for in design of the nozzle-chamber interface.

This technique satisfies the requirements of nozzle locking, which are as follows:

- The locking device must be designed fail safe. That if power is lost or interrupted, the ability to translate the nozzle extension is not impaired.

- Locking will not be affected by environmental conditions (space and earth).

- Devices will be located in a cool zone and unaffected by heat soak-back from engine operation, eliminating possible binding due to thermal expansion of the nozzle extension

- Nozzle lock and unlock shall be upon command That the locking mechanism cannot possibly unlock until signaled to do so

- The same locking device should be used for locking the nozzle in the extended or stowed position, eliminating the need for two of the same or possibly different devices or techniques

V, B, Design Considerations (cont)

The only other concern is the cold welding which takes place in the vacuum of space between certain metal pairs   This problem can be aleviated through the use of select soluble metal couples, such as copper/molybdenum or silver/ nickel, or lubricants developed for space use

3   Space Lubricants

Several different types of lubricants currently are available which have been developed and found suitable for elevated temperature operation in the space vacuum as well as standard conditions. These lubricants are required in at least two specific areas of the deployable nozzle system   The first is the inter-face between the threaded lugs and shaft (Figure 22), and second is the interface between the movable nozzle extension and alignment springs (Figures 1 and 22) on the fixed nozzle which accomplish final alignment.

The types of lubricants now available, which are most suited to this rubbing or sliding type of friction, are the so-called bonded solid films and the dry powder lubricants which are usually sprayed on the metal surface

The most promising solid bonded and dry powder lubricants available make use of molybdenum disulfide (MoS_2) either alone or in combination with other constituents   The bonding agent for the solid bonded type can be a resin or polyi-mide or boric oxide (B_2O_3)   The dry powder types are applied by several methods with impingement plating being the most popular

The solid bonded types which have undergone extensive testing under different environmental conditions are   (1) $PbS-MoS_2-P_2O_3$ and (2) MoS_2-SbO_3-polyimide (MIL-MLR-2)   Both exhibit good wear life and low friction coefficients from -100°F to 1000°F at standard and vacuum conditions   In general, friction decreases and wear life increases at higher temperatures and reduced atmosphere

V, B, Design Considerations (cont.)

One of the better dry powder lubricants which has successfully been used in the Apollo and other space programs is Microseal 200-1 (MIL-L-8937), manufactured by the Microseal Corporation. This compound uses MoS_2 as its lubricating solid and is applied by an impingement plating process proprietary to Microseal

Both the solid and dry powder lubricants are applied or deposited to depths ranging from 0.0001 to 0 001 in , depending on the usage and the material to which the lubricant is being applied Surface preparation of the material is usually very exacting with very smooth, treated surfaces required for good adhesion or dispersion.

C.   SELECTED APPROACH - TRANSLATION SYSTEM DESIGN

1.   Description

The selected concept considered as best filling the requirements and conclusions discussed in the previous section is shown in Figures 21 and 22 It consists of three (for system stability) tubular steel jack screws which are driven by electric motors The three jack screws are located 120° apart as shown in Figure 21.

Twenty-eight volt motors are used which have integral spur reduction gear sets. The mounting flange is also integral with the housing. The motor is mounted to the engine structure by means of an elastomeric, flexible load cell type of device similar to those used to mount engines in aircraft or automobiles

The hollow steel screw is mounted in an elastomeric-supported plain sleeve bearing located in the flange brazed to the tube bundle fixed section of the nozzle as shown in Figure 22. The other end of the threaded shaft is rigidly connected to the motor gearbox output shaft, the result being that the shaft is simply supported at both ends. The hollow tube can also be used to pipe a secondary coolant to the attachment joint region

V, C, Selected Approach - Translation System Design (cont)

The moving extension is attached to and supported by the mounting ring which has integral threaded lugs or nuts which the threaded shafts pass through The extension is therefore guided, supported, and translated by the threaded shaft

In order to maintain shaft synchronization during operation and to provide redundancy in case of a single motor failure, each shaft has incorporated on it a pulley for use with a timing belt which passes around all the shafts. This represents the basic translation system

2   System Redundancy

The tradeoff studies recommended that a redundant system be added which would retract the extension in the case of a complete power failure   Looking at the problem realistically, however, it is difficult to imagine a situation in which total craft power is lost and the urgency of the situation is not far greater than that of retracting a nozzle extension   Additionally, since the circuitry for engine control because of the location, it is difficult to imagine an accidental occurrence disrupting power to the drive motors without disrupting engine operation-- a far greater emergency than an extended nozzle   The situation seems to then concern itself with assuring reliable operation as long as power is available

It is likely that all of the mechanical components can be designed to function reliably and the problem, therefore, is concerned with an electrical failure (say, an open circuit) in the windings or coils of one of the motors   This failure mode is protected against by giving any two motors the capability of retracting the system, merely rotating the third motor armature and shaft by means of the synchronizing belt

3   System Loads

Assuming that the extension is translated only during nonfiring periods, what then are the loads that the translation system must withstand and overcome by the motor and jackscrew?

V, C, Selected Approach - Translation System Design (cont.)

The first load consideration is the friction forces due to turning the shaft in the support nuts and the bearings and/or bushings. Assuming that the shafting has been designed structurally capable of supporting the extension against external acceleration loads, these loads merely increase the resistance torque due to friction. If the threaded shaft is made of steel and the ring mount and nuts of titanium and the surface of the threaded shaft is treated with a dry powder lubricant such as described in Section V,B,3, the friction loads can be reduced to a small value

Recent work in which molybdenum disulfide was placed in the matrix of a pressed and sintered refractory metal has proven to provide an excellent lubricated bushing or wear resistant material.

It is possible that threaded inserts made of these materials could be placed in the mounting ring lug to ride the threaded shafts and that the ends of the shafts could be supported in plain bushings of the same material

It can be appreciated that the largest loads, friction or otherwise, which must be overcome are probably those associated with the vehicle setting on the earth during system checkout--and then primarily if the nozzle happens to be in a vertical position. It is unlikely that, when the nozzle is being deployed in space, there will be any "g" loads to be overcome and, therefore, the system may have to be designed for the "worst" case of deployment which is on earth

The force available with the system is high. For instance, a 1/5 HP motor with a 5 1 spur gear reduction delivers about 5 lb-in of torque at 500 rpm continuously at 28 VDC. If a threaded shaft having a 1-12 UNF thread is attached to it, each motor and shaft can move about 200 lb at a speed of about 40 in./minute, neglecting system friction

V, C, Selected Approach - Translation System Design (cont)

For the jackscrew design illustrated, the diameter is 1 in and there are 12 threads to the inch   Then for one revolution, the axial motion of the load is 1/12 of an inch or 0.0833 in., having ridden up a ramp 1 in or 3 1416 in and length
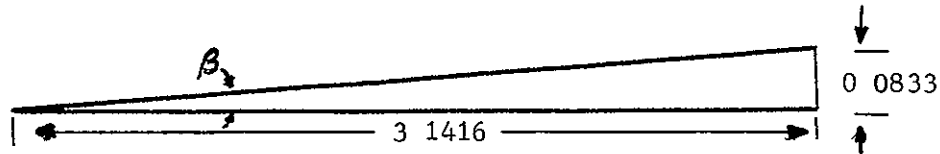
The tan of β = 0 0833/3 1416 = 0 0265 and therefore $\beta \cong$ 1 5° = jackscrew lead angle

With a jackscrew, any load translated forms a resisting torque to the rotation of the screw through friction which is proportional to the load acting along the thread or ramp   For a load, W, and a coefficient of friction, f, the friction force along the ramp or thread shown above is

$$F = W \times f \times \cos \beta = W \times f \times 0.99965 \cong W \times f$$

This friction force is located on a 1/2 in radius and therefore the friction torque is Wf/2 lb-in

The torque available in the electric motor for the system illustrated was 5 lb-in and f for the molybdenum disulfide impregnated refractory metal sintered bearings suggested for use is 0 05 in vacuum or air, at room temperature or up to 2200°F. Therefore, the weight or load that one jackscrew can move is just less than the weight found by the equations

Friction torque = Motor torque

$$\frac{Wf}{2} = \text{Motor torque}$$

$$W = \frac{\text{motor torque} \times 2}{f} = \frac{5 \times 2}{0\ 05} \text{ lb}$$

$$= 200 \text{ lb}$$

V, G, Selected Approach - Translation System Design (cont)

Therefore, the three jackscrew translation system proposed would be capable of lifting slightly less than 600 lb   This is for the "worst case" ground checkout since translation in space would be for essentially a no-load condition

The final question is whether or not the jackscrew system is capable of holding the extension in place against thrust loads without keeping the motor energized   If the inertia of the system is neglected, we are really asking if the load will slide back down the ramp or thread, causing the jackscrew to rotate

It was shown above that the tangent of the equivalent ramp angle , for the 1-12 UNF jackscrew illustrated was tan $\beta = 0\ 0265$ By definition, the coefficient of friction is defined as the tangent of an angle for which a load will just slide down a ramp.

Since $\tan^{-1} 0.0265$ or $1\ 5^{o}$ is less than $\tan^{-1} 0.05$ or 3°, the load cannot slide and it can be seen that the 1-12 UNF jackscrew with a coefficient of friction of 0.05 can support or hold by friction against any load up to the point where the jackscrew fails.

It can readily be seen that, in space, if no "g" loads are present, one motor of a three system could readily rotate all three shafts and move the largest extension within the limits of this program   It is only in a gravity field that motor size to accomplish translation becomes an important criterion

It is assumed that a motor should be selected which is suitable for vacuum operation as regards bearings, arcing, etc   If arcing of brushes is a severe problem, the use of synchronous AC motors should be investigated

V, C, Selected Approach - Translation System Design (cont)

4. Locking

The system is self-locking, that is, there is enough friction present in the system to prevent firing loads acting upon the extension in an axial direction to rotate the shafts, gears, armatures, etc   Travel is controlled in each direction by limit switches which open the motor circuit

Mounting each end of each shaft in an elastomeric holders allows a pretension to be put on the timing belt and also allows the nozzle some radial movement as it centers around the alignment springs and expands thermally

There is no size limitation to the approach so long as the shafting and bushings can support the extension and the motors can move it in at least a vertical mode on the ground for checkout purposes and maintenance

It should be remembered that the extension is best supported near the ends of the shaft, that is, in the retracted or extended position   In the center of travel, especially in a "g" field, the nozzle weight can be allowed to sag or cause a slight deflection in the shafting as long as binding does not occur. This is allowed because of the flexible end supports. If sagging or deflection of the shafting is not desirable for any reason, the threaded shaft can be cut and then spliced together through a supported bushing whose outer diameter is less than the minimum thread diameter   The nut or lug on the mounting ring can then be slotted to allow it to pass by the intermediate support

VI. SUPPORTING DESIGN ANALYSIS

A. STRUCTURAL ANALYSIS

Experience in the analysis of thrust chamber components has shown that, while pressure distribution is an important design consideration, operation temperatures and temperature gradients pose the most severe structural problems

Finite element analysis computer programs presently used in structural analysis can assist and can readily handle these thermal and pressure design problem

The mechanical characteristics of the materials employed are most important for stress analysis. Metals are generally well covered by the standard references as MIL-HDBK-5, Aerospace Structural Materials Handbook", and supplier data sheets.

The finite element method of analysis is applied to the determination of displacements and stresses within plane or axisymmetric with linear or nonlinear material properties. The continuous body is replaced by a system of elements of triangular or other cross section Since the elements are of arbitrary shapes and material properties, the procedure may be applied to structures comprised of many materials and configurations.

In the finite element approximation, the continuous structure is replaced by a system of elements which are interconnected at joints or nodal points Equilibrium equations, in terms of unknown displacements of the nodal point, are developed at each joint. Solution of this set of equations constitutes solution of the system

VI, Supporting Design Analysis (cont.)

B.   THERMAL DESIGN MODEL

Necessary design information includes specification of the temperatures of all parts of the system. This information affects the selection of materials, sealing methods and the geometry of the part   The temperature distribution within each part of the system is determined by means of a thermal model   The degree of complexity of the thermal model can vary greatly, depending on the detail with which it is necessary to predict temperatures and thermal gradients   Possible models range from simple one-dimensional energy balances to three-dimensional transient models in which conduction, convection, and radiation are considered Usually the development of a complete thermal model is an evolutionary process which takes place as the nozzle system proceeds from conceptual design, to detail design, and finally to development   The analytical model is tuned by using empirical methods to bring the thermal model into close agreement with experimental data   Once developed, the thermal model can be used to predict the effect of varying duty cycles and engine-vehicle environment changes in the system thermal performance

HIGH TEMPERATURE METALS

Material	Melting Point	Thermal Expansion	Oxidation Resistance	Thermal Conductivity	Specific Heat	Specific Gravity	Price
Tungsten	6170	2 2	Fair	96 6	0 034	19 4	12 5
Tantalum	5425	--	Good	31.5	0 036	16 6	55
Molybdenum	4750	--	Poor	84.5	0 065	10 2	20
Columbium	4620	--	Good	42	0 074	10 8	45
Rhodium	3571	--	Poor	50	0 059	12 4	2700
Hafnium	3400	3 4	Poor	--	0 035	13	120
Zirconium	3355	3 6	Poor	9 6	--	--	--
Thorium	3180	6.1	Poor	21 4	0 03	11 6	--
Vanadium	3110	--	Poor	--	0 12	6 4	3 9
Titanium	3040	71	Poor	9 8	0 13	4 73	3
Palladium	2829	6 5	Good	41	0 058	12	450
Martensitic Stainless	2800	6.5	Good	--	0 11	7.75	--
Ferritic Stainless	2790	7.9	Good	15 1	0 12	7 75	0 5
Carbon Steel	2775	--	Good	--	0 11	7 83	0 06
Cast Stainless	2750	10 4	Good	14 5	0 14	7 99	--
Cobalt	2723	--	--	--	--	8 86	--
Nickel Alloys	2635	9.2	Good	--	--	--	2
Beryllium	2341	6.4	Poor	87	0 45	--	70
Units	^{o}F	$^{o}F \times 10^{6}$	--	$\dfrac{Btu}{hr\text{-}ft\text{-}^{o}F}$	$\dfrac{Btu}{lb\text{-}^{o}F}$	--	\$/lb

Table I

DELIVERED PERFORMANCE, R_T = 1.28 in.

a P_c = 300 psia

	ε = 80 L/L Minimum			ε = 140 L/L Minimum			ε = 180 L/L Minimum			ε = 240 L/L Minimum			ε = 280 L/L Minimum			ε = 300 L/L Minimum		
	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50
ISP, THEO	461.4	461.4	461.4	470.2	470.2	470.2	473.7	473.7	473.7	477.4	477.4	477.4	479.2	479.2	479.2	479.9	479.9	479.9
ISP, ODK	449.2	449.6	449.9	456.7	457.2	457.4	459.6	460.1	460.4	462.7	463.2	463.5	464.2	464.7	464.9	464.9	465.4	465.8
ISP, TBL	3.32	3.43	3.82	4.06	4.53	5.01	4.95	5.51	6.10	5.96	6.65	7.35	6.45	7.19	7.95	6.64	7.41	8.06
ISP, DIV	6.17	2.01	0.41	4.84	1.58	0.23	4.46	1.45	0.14	4.06	1.32	0.09	3.84	1.23	0.05	3.76	1.20	0.04
ISP, COOL	0.84	0.84	0.84	1.08	1.08	1.08	1.05	1.05	1.05	1.02	1.02	1.02	1.01	1.01	1.01	1.00	1.00	1.00
ISP, ERL	4.61	4.61	61	4.70	4.70	4.70	4.74	4.74	4.74	4.77	4.77	4.77	4.79	4.79	4.79	4.80	4.80	4.80
ISP, DEL	434.3	438.8	440.2	442.0	445.3	446.4	444.7	447.4	448.4	446.9	449.5	450.2	448.1	450.5	451.1	448.7	451.0	451.9

b P_c = 500 psia

	ε = 80 L/L Minimum			ε = 140 L/L Minimum			ε = 180 L/L Minimum			ε = 240 L/L Minimum			ε = 280 L/L Minimum			ε = 300 L/L Minimum		
	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50
ISP, THEO	462.1	462.1	462.1	470.8	470.8	470.8	474.2	474.2	474.2	477.9	477.9	477.9	479.7	479.7	479.7	480.6	480.6	480.6
ISP, ODK	454.0	454.4	454.6	461.7	462.2	462.4	464.8	465.2	465.4	467.9	468.4	468.6	469.5	470.0	470.2	470.1	470.7	470.9
ISP, TBL	3.00	3.10	3.45	3.67	4.09	4.53	4.47	4.98	5.51	5.38	6.00	6.64	5.82	6.48	7.17	5.99	6.67	7.38
ISP, DIV	6.18	2.01	0.41	4.85	1.58	0.23	4.46	1.46	0.41	4.07	1.32	0.09	3.85	1.23	0.05	3.76	1.20	0.04
ISP, COOL	1.59	1.59	1.59	1.75	1.75	1.75	1.71	1.71	1.71	1.67	1.67	1.67	1.66	1.66	1.66	1.65	1.65	1.65
ISP, ERL	4.62	4.62	4.62	4.71	4.71	4.71	4.74	4.74	4.74	4.78	4.78	4.78	4.80	4.80	4.80	4.80	4.80	4.80
ISP, DEL	438.6	443.0	444.5	446.7	450.1	451.2	449.4	452.3	453.3	452.0	454.6	455.4	453.3	455.8	456.5	453.9	456.4	457

Table II
Sheet 1 of 1

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DELIVERED PERFORMANCE, R_T = 1 28 in   (Cont)

P_c = 1000 psia

Table II
Sheet 2 of 2

	ϵ = 80 L/L Minimum			ϵ = 140 L/L Minimum			ϵ = 180 L/L Minimum			ϵ = 240 L/L Minimum			ϵ = 280 L/L Minimum			ϵ = 300 L/L Minimum		
	1	1 25	1 50	1	1 25	1 50	1	1 25	1 50	1	1 25	1 50	1	1 25	1 50	1	1 25	1 50
ISP, THEØ	462 9	462 9	462 9	471 5	471 5	471 5	474 9	474 9	474 0	478 4	478 4	478.4	480 2	480 2	480.2	480 9	480 9	480 9
ISP, ØDK	458 7	459 0	459 1	466 8	467 1	467 2	470 0	470 3	470 4	473 2	473.6	473 7	474 9	475 2	475 4	475 5	475.9	476.1
ISP, TBL	2 61	2 70	3 00	3 20	3 56	3 94	3 89	4 33	4 80	4 68	5 22	5 78	5 07	5.65	6.25	5 21	5 82	6 43
ISP, DIV	6 19	2 02	0 41	4 85	1 59	0 23	4 47	1 46	0 14	4 07	1 33	0 09	3 85	1 24	0 05	3 75	1 21	0 04
ISP, CØL	3 10	3 10	3 10	3 36	3 36	3 36	3 32	3 32	3 32	3.27	3 27	3 27	3.25	3 25	3.25	3 25	3.25	3 25
ISP, ERL	4 63	4 63	4 63	4 71	4 71	4 71	4 75	4 75	4 75	4 78	4 8	4 78	4 80	4 80	4.80	4 80	4 80	4 80
ISP, DEL	442 2	446 5	448 0	450 7	453 9	455 0	453 5	456 4	457 4	456 4	458 8	459 3	457 9	460 3	461 0	458.5	460.8	461.6

DELIVERED PERFORMANCE, R_T = 1.81 in.

Table III
Sheet 1 of 2

a
P_c = 300 psia

	ϵ = 80 L/L Minimum			ϵ = 140 L/L Minimum			ϵ = 180 L/L Minimum			ϵ = 240 L/L Minimum			ϵ = 280 L/L Minimum			ϵ = 300 L/L Minimum		
	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50
ISP, THEØ	461.4	461.4	461.4	470.2	470.2	470.2	473.7	473.7	473.7	477.4	477.4	477.4	479.2	479.2	479.2	479.3	479.8	479.0
ISP, ØDK	450.4	450.9	451.1	458.0	458.5	458.7	461.0	461.5	461.7	464.1	464.6	464.9	465.6	465.1	466.4	466.2	466.8	467.0
ISP, TBL	2.86	2.96	3.29	3.50	3.91	4.32	4.27	4.75	5.26	5.14	5.74	6.34	5.56	6.20	6.86	5.72	6.37	7.05
ISP, DIV	6.17	2.01	0.41	4.84	1.58	0.23	4.46	1.45	0.14	4.06	1.32	0.09	3.84	1.23	0.05	3.75	1.20	0.04
ISP,CØØL	0.92	0.92	0.92	1.01	1.01	1.01	0.99	0.99	0.99	0.97	0.97	0.97	0.90	0.90	0.90	0.85	0.85	0.85
ISP, ERL	4.61	4.61	4.61	4.70	4.70	4.70	4.74	4.74	4.74	4.77	4.77	4.77	4.79	4.79	4.79	4.80	4.80	4.80
ISP, DEL	435.9	440.4	441.9	444.0	447.3	448.5	446.5	449.6	450.6	449.1	451.8	452.7	450.5	453.0	453.8	451.1	453.6	454.3

b
P_c = 500 psia

	ϵ = 80 L/L Minimum			ϵ = 140 L/L Minimum			ϵ = 180 L/L Minimum			ϵ = 240 L/L Minimum			ϵ = 280 L/L Minimum			ϵ = 300 L/L Minimum		
	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50	1	1.25	1.50
ISP, THEØ	462.1	462.1	462.1	470.8	470.8	470.8	474.2	474.2	474.2	477.9	477.9	477.9	479.7	479.7	479.7	480.3	480.3	480.3
ISP, ØDK	455.0	455.4	455.6	462.8	463.3	463.5	465.9	466.3	466.6	469.0	469.5	469.8	470.6	471.2	471.4	471.4	471.8	472.0
ISP, TPL	2.59	2.67	2.98	3.17	3.53	3.91	3.89	4.30	4.75	4.64	5.17	5.73	5.02	5.59	6.18	5.18	5.75	6.37
ISP, DIV	6.18	2.01	0.41	4.85	1.58	0.23	4.46	1.46	0.14	4.01	1.32	0.09	3.85	1.23	0.05	3.76	1.21	0.04
ISP, CØØL	1.51	1.51	1.51	1.65	1.65	1.65	1.62	1.62	1.62	1.60	1.60	1.60	1.52	1.52	1.52	1.47	1.47	1.47
ISP, ERL	4.62	4.62	4.62	4.71	4.71	4.71	4.74	4.74	4.74	4.78	4.78	4.78	4.80	4.80	4.80	4.80	4.80	4.80
ISP, DEL	440.1	444.6	446.1	448.6	451.8	453.0	451.2	452.2	455.3	453.9	456.7	457.6	455.4	458.0	458.8	456.2	458.6	459.3

P_c = 1000 psia

c

	ϵ = 80 L/L Minimum			ϵ = 140 L/L Minimum			ϵ = 180 L/L Minimum			ϵ = 240 L/L Minimum			ϵ = 280 L/L Minimum			ϵ = 300 L/L Minimum		
	1	1 25	1 50	1	1.25	1 50	1	1.25	1 50	1	1 25	1 50	1	1 25	1 50	1	1 25	1 50
ISP, THEO	462 9	462 9	462 9	471 5	471 5	471 5	474 9	474 9	474 9	478 4	478 4	478.4	480.2	480 2	480 2	480 8	480 8	480 8
ISP, ODK	459.3	459 6	459 7	467 5	467 8	467 9	470 7	471 0	471 1	474 0	474 3	474 5	475 6	476 0	476 1	476.2	476 6	476 8
ISP, TBL	2 25	2 33	2 59	2 76	3 07	3 40	3 35	3 73	4 14	4 04	4 50	4 98	4 37	4 87	5 39	4 50	5.02	5 56
ISP, DIV	6.19	2 02	0.41	4 85	1 59	0 23	4 47	1 46	0 14	4 07	1.33	0 09	3 85	1 24	0 05	3 76	1 22	0 04
ISP, COOL	2 98	2 98	2 98	3.20	3 20	3 20	3 18	3 18	3.18	3 15	3 15	3 15	3 04	3 04	3 04	2 97	2 97	2 97
ISP, ERL	4 63	4 63	4 63	4 72	4 72	4 72	4 75	4 75	4 75	4 78	4 78	4 78	4 80	4.80	4.80	4 80	4.80	4.80
ISP, DEL	443 3	447 6	449 1	452 0	455 2	456.4	454 9	457 8	458 9	457 0	460.6	461 5	459 6	462 0	462.8	460.2	462.6	463 4

Table III
Sheet 2 of 2

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RAO NOZZLE CONTOURS

AREA RATIO = 80, MINIMUM LENGTH

R/R_t	Z/R_t	Surface* Area, in^2
1.0000	.00000	.00000
1.2138	.61802	7 3548
1.2690	68877	8 5044
1 3558	80046	10 420
1.4484	.92026	12 610
1 5480	1.0501	15 138
1 6585	1 1925	18 093
1 7769	1 3493	21 562
1.9054	1 5233	25 666
2 0479	1 7185	30 572
2.2037	1.9379	36 460
2 3756	2.1864	43 579
2.5665	2 4698	52 264
2 7784	2.7952	62.942
3.2321	3 5331	89.719
3 5423	4.0718	111 39
3 9823	4.8869	147 24
4.4115	5 7450	188.69
4 7865	6.5492	230.69
5.0688	7.1906	266.23
5.2807	7 6936	295 30
5.6019	8.4934	343 58
5.9260	9 3497	397.90
6 1193	9.8859	433 24
6 4607	10.881	501.37
6 7200	11 682	558.48
6.9155	12.314	604 93
7 2120	13.322	681 33
7 5107	14 403	766 32
7 7149	15 184	829 60
7.8938	15.899	888 80
8 2089	17.234	1002.5
8 4448	18.304	1096.4
8.7994	20 045	1254 1
8.9435	20.810	1325 2

* For R_t = 1.28 inches, Surface Area is Proportional to R_T^2

Table IV
Sheet 1 of 15

RAO NOZZLE CONTOURS (cont)

AREA RATIO = 80, 125% MINIMUM LENGTH

R/R_t	Z/R_t	Surface* Area, in^2
1 0000	00000	00000
1 1632	.54756	6 2935
1.1868	58358	6 8145
1 2529	.68392	8 3239
1 3237	79031	10 017
1 3995	.90435	11 938
1 4817	1 0277	14 135
1 5711	1 1622	16 673
1 6687	1 3103	19 632
1 7765	1 4747	23 113
1 8948	1 6581	27 238
2 0257	1 8641	32 164
2 1709	2 0969	38 089
2 3322	2 3618	45 277
2 5122	2 6655	54 078
2 9003	3 3523	76 039
3 1666	3.8528	93 739
3 5464	4.6092	122 98
3 9192	5 4056	156.76
4 2466	6.1524	191 03
4 4937	6 7480	220 04
4 6799	7.2156	243 80
4 9629	7 9597	283 31
5 2496	8 7574	327 86
5 4211	9 2573	356 89
5 7248	10 186	412 96
5 9561	10 935	460 05
6.1311	11 526	498 44
6 3972	12.470	561 69
6 6658	13 484	632 20
6 8501	14 217	684 81
7 0118	14.889	734 11
7 2975	16.145	828 97
7 5120	17.153	907 53
7 8356	18 795	1039 8
8 1560	20 591	1189 9
8 3433	21.733	1288 2
8 5054	22 788	1380 7
8 6459	23 757	1467 2
8 8874	25.562	1631 6
8 9432	26 011	1673 1

* For R_T = 1.28 inches, Surface Area is Proportional to R_T^2

Table IV
Sheet 2 of 15

RAO NOZZLE CONTOURS (cont)

AREA RATIO = 80, 150% MINIMUM LENGTH

R/R_t	Z/R_t	Surface Area[*], in^2
1 0000	00000	.00000
1 1414	51257	5 8039
1 1833	.58242	6 7788
1 2428	68037	8 2101
1 3066	78435	9 8112
1 3754	89561	11 617
1 4500	10158	13.674
1 5311	1 1469	16.040
1 6201	1 2910	18.786
1 7181	1 4506	22 004
1 8264	1 6287	25 804
1 9461	1 8284	30 324
2 0788	2.0537	35 741
2 2264	2 3096	42.287
2 3910	2 6025	50 271
2 7463	3.2636	70 105
2 9905	3 7444	86 026
3 3387	4 4698	112.24
3 6812	5 2330	142 45
3 9818	5.9476	173 03
4 2091	6.5177	198 90
4 3802	6.9649	220 07
4 6407	7 6765	255 26
4 9049	8 4393	294 91
5 0629	8 9173	320 74
5 3429	9 8056	370 63
5 5562	10 521	412 52
5 7179	11 087	446 67
5 9634	11 990	502 92
6 2117	12 959	565 64
6 3820	13 661	612 44
6 5318	14 304	656 32
6 7960	15 505	740 70
6 9946	16.470	810 59
7 2945	18.041	928 26
7 5917	19.759	1061 9
7 7655	20.852	1149 3
7 9160	21 861	1231 6
8 0464	22 787	1308 5
8 2708	24.513	1454 7
8 4344	25 898	1574 6
8 6713	28 145	1773 5
8 8917	30 578	1994 4
8 9432	31 213	2052 9

* For R_T = 1.28 inches, Surface Area is Proportional to R_T^2

Table IV
Sheet 3 of 15

RAO NOZZLE CONTOURS (Cont)

AREA RATIO = 140, MINIMUM LENGTH

R/R$_t$	Z/R$_t$	Surface* Area , in^2
1 0000	00000	00000
1 2350	64407	7 7780
1 2733	68986	8 5506
1 3681	80379	10 571
1 4694	92620	12 897
1 5784	1 0591	15 599
1 6968	1 2048	18 767
1 8262	1 3661	22 520
1 9712	1 5464	27 015
2 1324	1 7492	32 435
2 3061	1 9775	38 981
2 4984	2.2368	46 957
2 7127	2 5336	56 763
2 9518	2 8758	68 923
3 4689	3 6572	99 848
3 8257	4.2316	125 22
4 3369	5 1065	167 76
4 8411	6 0344	217 63
5 2865	6 9099	268 8
5 6245	7 6114	312 54
5 8794	8.1633	348 53
6 2692	9 0449	408 80
6 6662	9. 9930	477 23
6 9048	10 589	522 07
7 3292	11.699	609 13
7 6542	12 596	682 68
7.9014	13 306	742 90
8.2788	14 442	842 55
8.6627	15 664	954 27
8 9277	16 550	1038 0
9 1616	17.363	1116 8
9 5772	18.886	1269 0
9.8921	20 111	1395 8
10 372	22.112	1610 4
10 855	24.307	1855 9
11 140	25 706	2017 7
11.390	27.001	2170 6
11 609	28.193	2314 0
11.832	29.476	2471 2

* For R$_T$ = 1.28 inches, Surface Area is Proportional to R$_T^2$

Table IV
Sheet 4 of 15

RAO NOZZLE CONTOURS (Cont)

AREA RATIO = 140, 125% MINIMUM LENGTH

R/R_t	Z/R_t	Surface Area*, in^2
1 0000	00000	00000
1 1793	57134	6 6394
1 1881	58395	6 8267
1 2595	68600	8 3961
1 3359	.79435	10 167
1 4183	91067	12 188
1 5076	1 0367	14 514
1 6052	1 1745	17 218
1 7121	1 3266	20 392
1 8300	1 4956	24 149
1 9605	1 6848	28 634
2 1055	1 8981	34 030
2 2669	2.1399	40 571
2 4472	2 4161	48 571
2 6495	2.7339	58 452
3 0893	3 4576	83 450
3 3947	3 9889	103 90
3 8343	4.7971	138 12
4 2711	5.6547	178 26
4 6585	6.4638	219 49
4 9539	7 1129	254 77
5 1778	7.6242	283 88
5 5207	8.4413	332 67
5 8713	9 3212	388 21
6 0829	9 8751	424 69
6 4601	10 908	495 67
6 7501	11 743	555 80
6 9710	12.406	605 13
7 3095	13 466	686 96
7 6552	14.610	778 99
7 8944	15.441	848 15
8,1060	16.203	913 34
8 4833	17 633	1039 6
8 7701	18 786	1145 1
9 2091	20.671	1324 3
9 6520	22 743	1530 0
9 9153	24.067	1665 9
10 146	25 293	1794 7
10 349	26.422	1915 7
10.704	28.534	2147 7
10.968	30.235	2339 8
11 360	33 012	2662 1
11 740	36 041	3025 1
11 832	36 847	3123 5

* For R_T = 1.28 inches, Surface Area is Proportional to R_T^2

Table IV
Sheet 5 of 15

RAO NOZZLE CONTOURS (Cont)

AREA RATIO = 180, MINIMUM LENGTH

R/R_t	Z/R_t	Surface* Area, in^2
1. 0000	00000	. 00000
1 2454	65623	7 9825
1 2748	. 69020	8. 5663
1 3736	. 80517	10 639
1 4791	92880	13 032
1 5928	1 0631	15. 820
1 7162	1. 2105	19 099
1 8513	1. 3738	22. 993
2 0001	1 5563	27 660
2 1644	1. 7618	33 298
2. 3545	1. 9959	40. 207
2. 5606	2 2616	48 648
2 7864	2. 5652	59. 035
3 0386	2. 9156	71 957
3 5859	3. 7178	105 00
3. 9646	4 3090	132. 26
4. 5089	5. 2115	178 18
5 0488	6. 1720	232 35
5. 5273	7. 0802	288 20
5. 8916	7. 8096	336 11
6. 1673	8 3843	375 66
6 5900	9. 3039	442 10
7. 0216	10 294	517 79
7. 2820	10. 918	567 55
7. 7464	12 082	664 45
8. 1033	13 023	746 58
8 3754	13 770	813 98
8. 7923	14. 965	925 85
9 2181	16. 254	1051 7
9 5128	17. 190	1146 3
9. 7737	18 050	1235 4
10. 239	19 662	1408 3
10 593	20. 960	1552 6
11. 137	23 085	1797 9
11. 686	25. 420	2079 6
12. 015	26. 912	2265 9
12 300	28. 293	2442.5
12. 553	29. 565	2608 5
12 996	31 946	2926 9
13. 328	33 866	3190 9
13. 417	34. 411	3267 0

* For R_T = 1.28 inches, Surface Area is Proportional to R_T^2

Table IV
Sheet 7 of 15

RAO NOZZLE CONTOURS (Cont)

AREA RATIO = 140, 150% MINIMUM LENGTH

R/R_t	Z/R_t	Surface Area[*] ,in^2
1 0000	00000	00000
1 1569	53771	6 1533
1 1861	58336	6 8071
1 2506	68307	8 2966
1 3199	78903	9 9717
1 3947	.90264	11 872
1. 4760	1 0256	14 050
1 5649	1 1599	16 571
1 6626	1 3079	19 516
1 7704	1 4722	22 987
1 8898	1 6559	27. 115
2 0224	1 8626	32 060
2 1702	2 0966	38 037
2 3355	2. 3034	45 309
2 5208	2 6699	54 261
2 9241	3 3661	76 796
3 2045	3.8762	95 153
3 6082	4 6510	125 78
4 0095	5 4718	161 59
4 3659	6 2457	198 32
4 6376	6.8660	229 70
4 8458	7 3547	255 58
5 1596	8 1352	298 93
5 1828	8 9757	348 26
5 6779	9 5047	380 65
6 0261	10 491	443 67
6 2938	11 289	497 01
6 4981	11 922	540 84
6. 8112	12 936	613 51
7 1311	14 029	695 24
7 3527	14 822	756 67
7 5487	15 552	814 56
7 8986	16 919	926 83
8 1647	18 021	1020 6
8 5724	19 825	1179 9
8 9842	21 808	1362 9
9 2291	23 075	1483 9
9 4142	24 248	1598 5
9 6330	25 329	1706 3
9 9635	27 350	1912 9
10 210	28 979	2083 9
10 577	31 636	2370 9
10 932	34 534	2694 0
11 168	36 694	2941 3
11 370	38 708	3176 1
11 540	40 573	3397 0
11 684	42 287	3602 6
11 832	44 212	3836 2

[*] For R_T = 1.28 inches, Surface Area is Proportional to R_T^2

Table IV
Sheet 6 of 15

RAO NOZZLE CONTOURS (Cont)

AREA RATIO = 180, 125% MINIMUM LENGTH

R/R_t	Z/R_t	Surface* Area, in^2
1 0000	00000	00000
1 1864	58146	6 7901
1 1882	58399	6 8283
1 2620	68676	8 4240
1 3410	79595	10 230
1 4263	91323	12 295
1 5188	1 0404	14 679
1 6199	1 1796	17 458
1 7310	1 3334	20 728
1 8537	1 5045	24 612
1 9897	1 6963	29 263
2 1409	1 9127	34 875
2 3096	2 1584	41 702
2 4983	2 4394	50 077
2 7106	2 7635	60 462
3 1742	3 5035	86 894
3 4974	4 0485	108.65
3 9647	4 8799	145 27
4 4313	5 7651	188 50
4 8471	6 6028	233 15
5 1652	7 2762	271 53
5 4069	7 8074	303 29
5 7783	8 6580	356 72
6 1595	9 5760	417 79
6 3901	10 155	458 02
6 8028	11 236	536 59
7 1209	12 111	603 37
7 3642	12 807	658 32
7 7381	13 922	749 75
8 1214	15 127	852 95
8 3876	16 003	930 75
8 6237	16 808	1004.2
9.0464	18 321	1147 1
9 3690	19.542	1266.8
9 8657	21 543	1470 9
10 370	23 747	1706 4
10 672	25 157	1862.6
10 938	26.464	2011.0
11 172	27 670	2150.8
11 585	29 982	2419.7
11.894	31 751	2643.1
12 359	34.732	3019.7
12 813	37 991	3446.0
13 120	40 429	3774 0
13 383	42 705	4086 7
13 417	43 014	4129 5

* For R_T = 1.28 inches, Surface Area is Proportional to R_T^2

Table IV
Sheet 8 of 15

RAO NOZZLE CONTOURS (Cont)

AREA RATIO = 180, 150% MINIMUM LENGTH

R/R_t	Z/R_t	Surface* Area, in^2
1 0000	00000	00000
1 1637	54830	6 3040
1 1870	8363	6 8157
1 2537	68409	8 3305
1 3254	79088	10 038
1 4029	90548	11 981
1 4872	1 0496	14 213
1 5794	1 1653	16 802
1 6809	1 3149	19 836
1 7930	1 4812	23 422
1 9175	1 6674	27 699
2 0561	1 8772	32 840
2 210o	2 1150	39 067
2 3838	2 3864	46 679
2 5784	2 6989	56 081
3 0057	3 4107	79 889
3 3003	3 9337	99 394
3 7295	4 7304	132 13
4.1582	5 5772	170 65
4 5465	6 3778	210 37
4 8533	7 0211	242 47
5 0558	7 5284	272 67
5 3979	8 3405	320 07
5 7492	9 2167	374 23
5 9618	9 7689	409 91
6 3428	10 801	479 56
6 6367	11 637	538 77
6 8616	12 301	587 49
7 2075	13 366	668 58
7 5622	14 517	760 11
7 8087	15 353	829 13
8 0276	16 123	894 35
8 4196	17 569	1021 2
8 7191	18 736	1127 4
9.1805	20 650	1308 8
9 6498	22 758	1518 2
9 9307	24 108	1657 1
10 178	25 359	1789 1
10 397	26 513	1913 6
10 782	28 675	2152 9
11 071	30 421	2351 9
11 505	33 274	2687 3
11 930	36 393	3067 0
12 218	38 725	3359 1
12 465	40 903	3637 5
12 676	42 924	3900 5
12 857	44 784	4146 2
13 162	48 262	4613 7
13.377	51 053	4996 0
13 417	51 615	5073 8

* For R_T = 1.28 inches, Surface Area is Proportional to R_T^2

Table IV
Sheet 9 of 15

AREA RATIO = 240, MINIMUM LENGTH

R/R_t	Z/R_t	Surface Area, in^2 *
1 0000	.00000	00000
1 2593	67183	8.2515
1 2761	69049	8 5801
1 3803	80680	10 723
1 4917	93200	13 206
1 6116	1 0682	16.112
1 7419	1 2178	19 542
1 8845	1 3838	23.631
2.0416	1 5695	28 547
2.2156	1 7788	34 507
2 4092	2 0166	41 792
2 6254	2 2885	50 765
2 8655	2.6014	61 896
3 1607	2.9698	76 093
3 7455	3 8002	112.05
4 1514	4 4132	141 85
4 7361	5 3504	192 28
5 3181	6.3502	252 06
5 8357	7 2975	313 96
6.2312	8 0598	367 26
6 5314	8.6614	411 40
6 9925	9 6253	485 74
7.4654	10.666	570 77
7 7516	11 322	626.82
8.2631	12.548	736 28
8 6579	13 542	829 39
8 9597	14.331	906 00
9.4237	15 596	1033.5
9.8992	16 963	1177 4
10.230	17.957	1285 9
10 523	18 871	1388 4
11 049	20.587	1587 7
11 450	21 972	1754 7
12.069	24 243	2039 6
12 700	26.744	2368 4
13.078	28 344	2586 6
13 412	29.828	2793.9
13 706	31 197	2989 3
14 226	33 761	3365 5
14.617	35.832	3678 4
15 207	39 220	4206 2
15.492	40 995	4490 4

* For R_T = 1.28 inches, Surface Area is Proportional to R_T^2

Table IV
Sheet 10 of 15

RAO NOZZLE CONTOURS (Cont.)

AREA RATIO = 240, 125% MINIMUM LENGTH

R/R_t	z/R_t	Surface* Area, in^2
1 0000	.00000	00000
1 1946	59280	6 9619
1.2641	.68754	8.4532
1.3467	.79766	10 299
1.4353	.91603	12 415
1.5315	1 0445	14 861
1 6367	1 1853	17 733
1 7526	1 3409	21 117
1.8807	1.5144	25 148
2 0229	1.7030	29 992
2.1814	1 9200	35 852
2 3586	2 1792	43 022
2 5575	2 4659	51 648
2.7811	2 7970	62.831
3.2128	3 5559	90 981
3 6169	4.1165	114.30
4.1170	4.9751	153.84
4.6186	5 8921	200 83
5.0680	6 7629	249 67
5.4130	7 4645	291.85
5.6760	8.0192	326 88
6 0813	8 9089	386 05
6 4990	9 8713	453.91
6 7525	10 479	498 89
7.2077	11.617	586 92
7 5601	12 540	662 06
7.8304	13.275	724 08
8 2471	14 455	827 62
8.6760	15 732	944 94
8.9750	16.652	1033 7
9 2410	17 518	1117.8
9 7191	19 128	1231 7
10 085	20.430	1419 6
10 653	22.569	1655 8
11 234	24.930	1929 7
11 583	25.445	2112 2
11 892	27.850	2286 1
12.166	29 148	2450.3
12.651	31.582	2767.4
13.017	33 551	3032 0
13 570	36 776	3479 9
14 121	40.312	3990 0
14 496	42.963	4384 3
14.821	45.443	4761 8
15 102	47.751	5119.8
15 345	49.879	5455.5
15 491	51.237	5672 3

* For R_T = 1.28 inches, Surface Area is Proportional to R_T^2

Table IV

Sheet 11 of 15

RAO NOZZLE CONTOURS (Cont.)

AREA RATIO = 240, 150% MINIMUM LENGTH

R/R$_t$	Z/R$_t$	Surface * Area, in^2
1.0000	.00000	00000
1.1716	56014	6 4751
1.1877	58384	6 8227
1.2569	68513	8 3665
1 3314	.79285	10 111
1 4120	90854	12 102
1 4997	1 0340	14 396
1 5958	1.1712	17 065
1 7017	1 3227	20 202
1 8189	1 4913	23 922
1 9491	1 6802	28 373
2 0943	1 8934	33 740
2.2507	2.1355	40 267
2 4390	2 4123	48 275
2 6444	2 7315	58 206
3 0949	3 4609	83 517
3.4108	3 9988	104 40
3 8697	4 8206	139 66
4 3306	5 6974	181 45
4.7434	6 5287	224 20
5.0607	7 1503	262 19
5.3027	7 7215	293 25
5 6779	8 5761	345 61
6 0607	9 4940	405 73
6.2944	10 073	445 47
6.7142	11 158	523 33
7 0396	12 039	585 81
7 2894	12 740	644 68
7 6745	13 865	736 29
8.0714	15.083	840 14
8 3484	15 971	918 75
8.5948	16 738	993 17
9 0581	18 326	1138 4
9 3784	19.570	1260 6
9.9054	21.614	1470 2
10 445	23 871	1713.3
10.771	25 320	1875.4
11 059	26 664	2029 9
11 314	27.905	2175.9
11 766	30 236	2457 8
12.105	32.120	2693 2
12.627	35.208	3091 9
13 141	38.594	3546 0
13.493	41 132	3897 3
13.798	43 505	4233 5
14 062	45 734	4552 4
14 290	47.750	4851 3
14 680	51.565	5423 2
14 961	54.636	5893 8
15 361	59 645	6677 9
15 491	61 483	6970 5

* For R$_m$ = 1 28 inches, Surface Area is Proportional to R$_m^2$

Table IV
Sheet 12 of 15

RAO NOZZLE CONTOURS (Cont)

AREA RATIO = 280, MINIMUM LENGTH

R/R_t	Z/R_t	Surface* Area, in^2
1.0000	.00000	.00000
1.2697	.68310	8.4510
1.2766	.69059	8.5853
1.3850	.80786	10 780
1.5003	93421	13.334
1.6255	1.0718	16 329
1.7610	1 2230	19 876
1 9094	1.3909	24 115
2.0729	1.5790	29 224
2.2539	1 7913	35.433
2 4553	2.0325	43 038
2.6797	2.3085	52.420
2.9348	2 6273	64.124
3 1889	2 9920	78.549
3 8634	3 8592	117 16
4 2944	4 4909	148 98
4.9038	5 4521	202 64
5.5102	6.4768	266 29
6.0498	7 4477	332 25
6 4624	8 2290	389.07
6 7759	8 8460	436 17
7 2580	9 8348	515 55
7.7531	10 903	606 44
8 0536	11.577	666 41
8.5902	12 837	763 67
9.0052	13 859	853.51
9.3830	14 673	965 75
9.8123	15 974	1102 8
10 315	17 383	1257 1
10 665	18.408	1374 6
10 976	19.351	1485.1
11.534	21 123	1700 4
11.961	22 554	1831 0
12.622	24.903	2189 7
13 297	27 493	2546 7
13 703	29 152	2784.1
14 062	30.692	3009 9
14 380	32 112	3223 0
14.942	34.777	3633 9
15.367	36.930	3975.3
16 030	40 457	4555.2
16.647	44.322	5213.6
16.733	44.881	5310.8

* For R_T = 1 28 inches, Surface Area is Proportional to R_T^2

Table IV
Sheet 13 of 15

RAO NOZZLE CONTOURS (Cont)

AREA RATIO = 280, 125% MINIMUM LENGTH

R/R_t	Z/R_t	Surface * Area , in^2
1.0000	00000	.00000
1 1995	.59928	7 0613
1 2661	68794	8 4689
1 3498	.79860	10 337
1 4404	91759	12 484
1 5388	1 0468	14 975
1 6464	1 1885	17 893
1 7650	1 3452	21 343
1 8963	1 5200	25 461
2 0421	1 7163	30 418
2 2049	1 9383	36 435
2 3870	2 1910	43 795
2 5914	2 4808	52.860
2 8222	2 8161	64 218
3 3252	3 5054	93 310
3 6855	4 1550	124 62
4 2040	5 0266	158 66
4.7251	5 9637	208 07
5 1942	6 8531	255 37
5 5645	7 5706	303 13
5 8507	8 1365	340 76
6 2715	9 0503	400 45
6 6950	10 038	475 52
6 9596	10 662	522 62
7 1592	11 151	616 69
7.5111	12 102	644 81
8 0933	13 538	763 03
8 5330	14 755	8 3 80
8 9931	16 012	934 40
9.3110	17 033	1004 9
9 5947	17 947	1115 3
10 104	19 583	1361 9
10 495	20 941	1510 8
11 104	23 148	1760 4
11 729	25 598	2063 5
12 105	27 171	2251 5
12 410	28 622	2451 2
12 736	30 982	2630 3
13 263	32 516	2710 7
13 652	34 568	3250 4
14 269	37 932	3757 9
14 874	41 625	4319 3
15 290	44 397	4754 4
15 651	46 993	5171 8
15 966	49 410	5568 5
16 238	51 641	5941 1
16 705	55 827	6655 7
16 734	56 107	6703 3

* For R_T = 1 28 inches, Surface Area is Proportional to r_T^2

Table IV
Sheet 14 of 15

RAO NOZZLE CONTOURS (Cont)

AREA RATIO = 280, 150% MINIMUM LENGTH

R/R_t	Z/R_t	Surface *$_2$ Area, in^2
1 0000	.00000	.00000
1 1761	.56669	6.5708
1 1880	58392	6.8255
1 2586	68567	8 3854
1.3347	79391	10 151
1 4170	.91019	12.169
1 5067	1 0363	14 498
1 6050	1 1744	17 212
1 7153	1.3269	20 408
1 8333	1 4968	24.203
1 9663	1 6873	28 752
2 1158	1 9023	34 249
2 2625	2 1467	40 945
2 4690	2 4264	49 178
2 6312	2 7494	59 411
3 1459	3 1886	85 582
3 1725	4 0346	107 25
3 9480	4.8703	143 96
4 4262	5 7636	187 64
4 8570	6 6121	233 09
5 1982	7 2564	272 39
5 4110	7 8376	305 07
5 8317	8 7055	360 35
6.2354	9 6473	423 93
6 6073	10 242	466 04
6 9227	11 356	548 72
7 2660	12 242	619 46
7 5223	12 543	677 94
7 9374	14 142	775.76
8 3582	15 398	886 87
8 6524	16 314	971 10
8 9146	17 158	1051 0
9 3671	18 748	1207 2
9 7507	20 035	1339 0
10 315	22 152	1565 2
10 855	24 492	1828 6
11 246	25 996	2004 5
11 558	27.392	2172 5
11 831	28 684	2331 4
12 325	31 108	2639 1
12 698	33.071	2896 4
13 266	36 291	3333 4
13 832	39 627	3832 9
14 221	42 481	4220 1
14.561	44 965	4591 7
14 856	47.279	4944 8
15 112	49 414	5276 5
15 522	53 420	5912 6
15 872	56.649	6437 5
16 333	61 925	7315 4
16 733	67 320	8236.1

* For R_T = 1 28 inches, Surface Area is Proportional to R_T^2

Table IV
Sheet 15 of 15

SECONDARY GAS COOLANT PROPERTIES AND ENGINE
AND GAS GENERATOR OPERATING CONDITIONS

SECONDARY GAS COOLANT PROPERTIES

$$T_o = 860°R$$

$$c^* = 4735 \text{ ft/sec}$$

$$r = 1\ 40$$

$$A^* = 2\ 407 \text{ in}^2$$

$$P_{o,\ turbine} = \frac{(c^*)\ (w)}{(A^*)\ (q_c)}$$

ENGINE AND GAS GENERATOR OPERATING CONDITIONS

	P_c (psia)	Mass Flow Rates (lbm/sec)	
		Thrust Chamber	Gas Generator Combustor
$R_t = 1\ 28$ in	300	6 71	0 028
	500	11 11	0 0778
	1,000	22 09	0 311
$R_t = 1\ 81$ in	300	13 42	0 056
	500	22 2?	0 1566
	1,000	44 18	0 622

Table V

Figure 1

Mounting Ring

Alignment Spring Clips

C-103 Extension

Minimum Discontinuity Cross Flow Cooled Tip

Secondary Coolant Injection Ports

Silicon Rubber Gasket

Secondary Coolant Inlet

A-286 Tube Bundle 1 1/2 Pass Fixed Section

Spring Fabrication
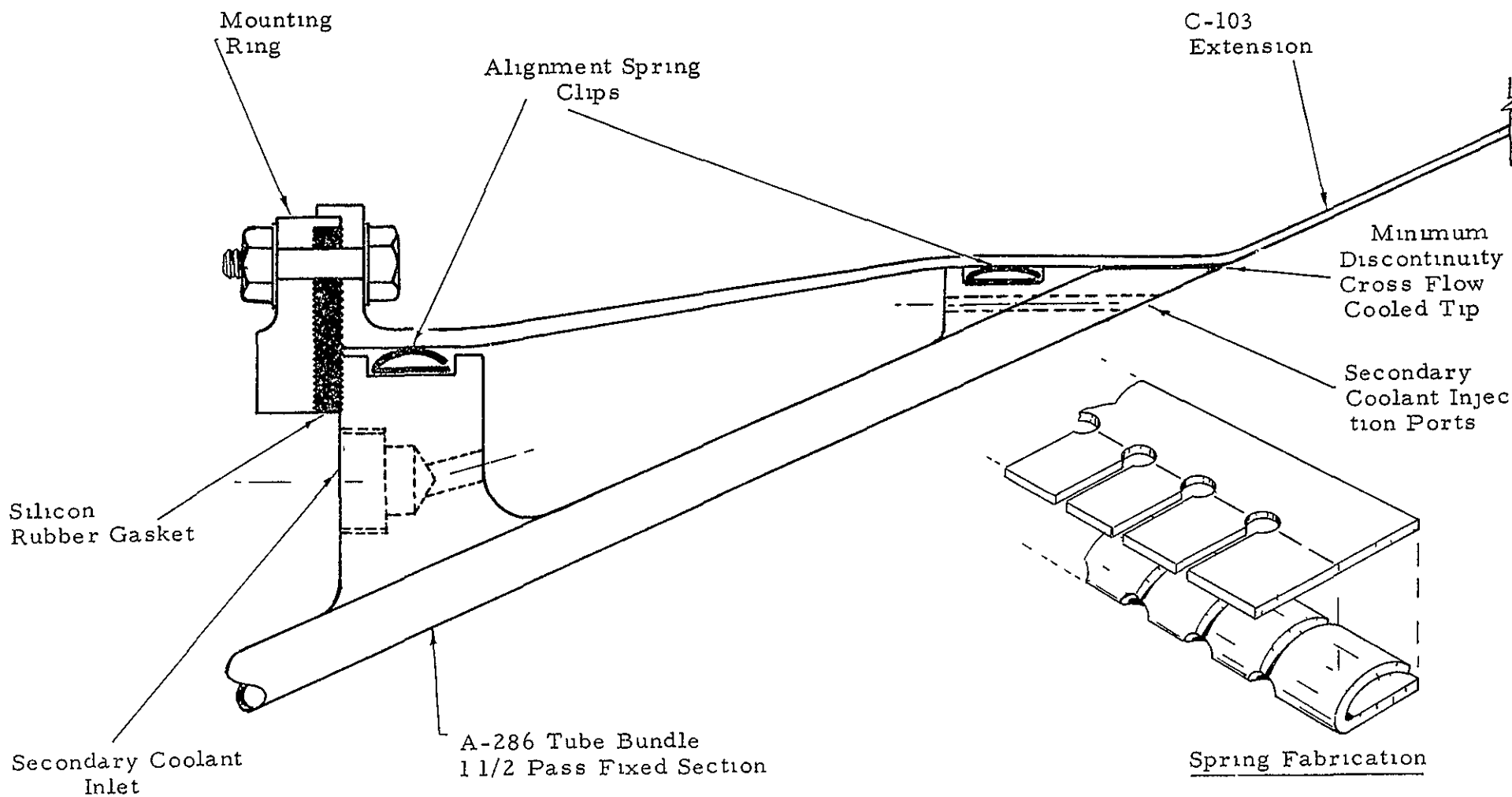
EXTENSION ALIGNMENT SPRINGS

Typical
Streamline

Prandtl-Meyer
Expansion

Reattachment
Shock

Prandtl-Meyer
Expansion

Separated Flow
Region

Reattachment Point
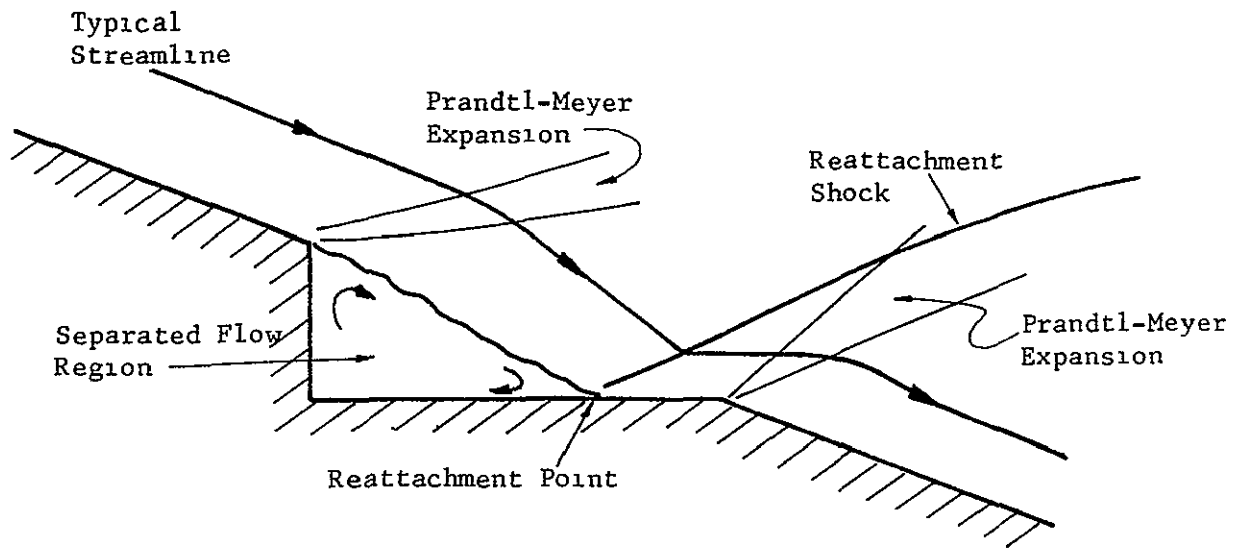
a.   Extendable Nozzle attachment Joint Wall Discontinuity

Rearward Facing Step

Forward Facing Step

Open Cavity
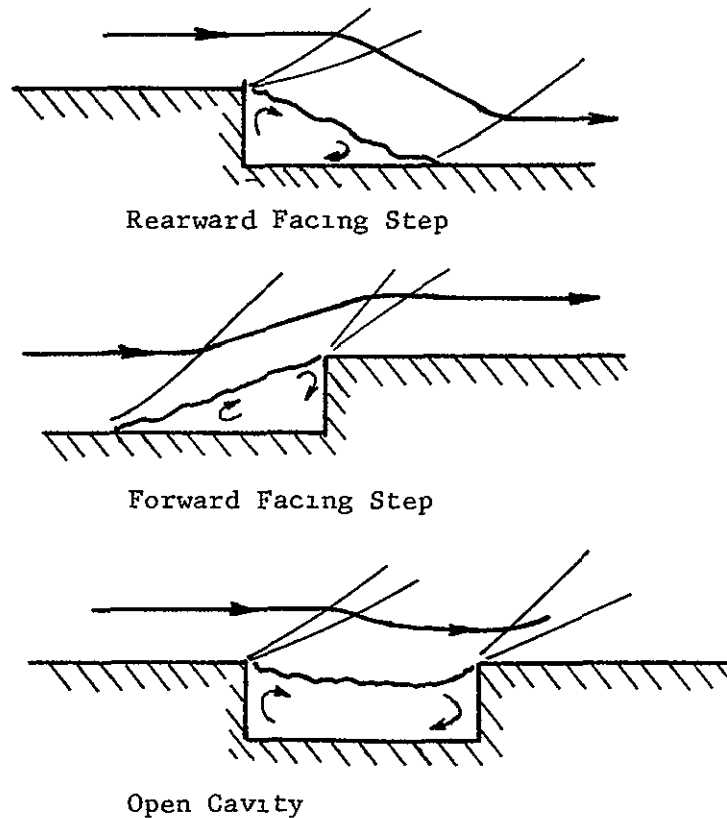
b   Typical Wall Discontinuities

WALL DISCONTINUITIES

Figure 2

Figure 3
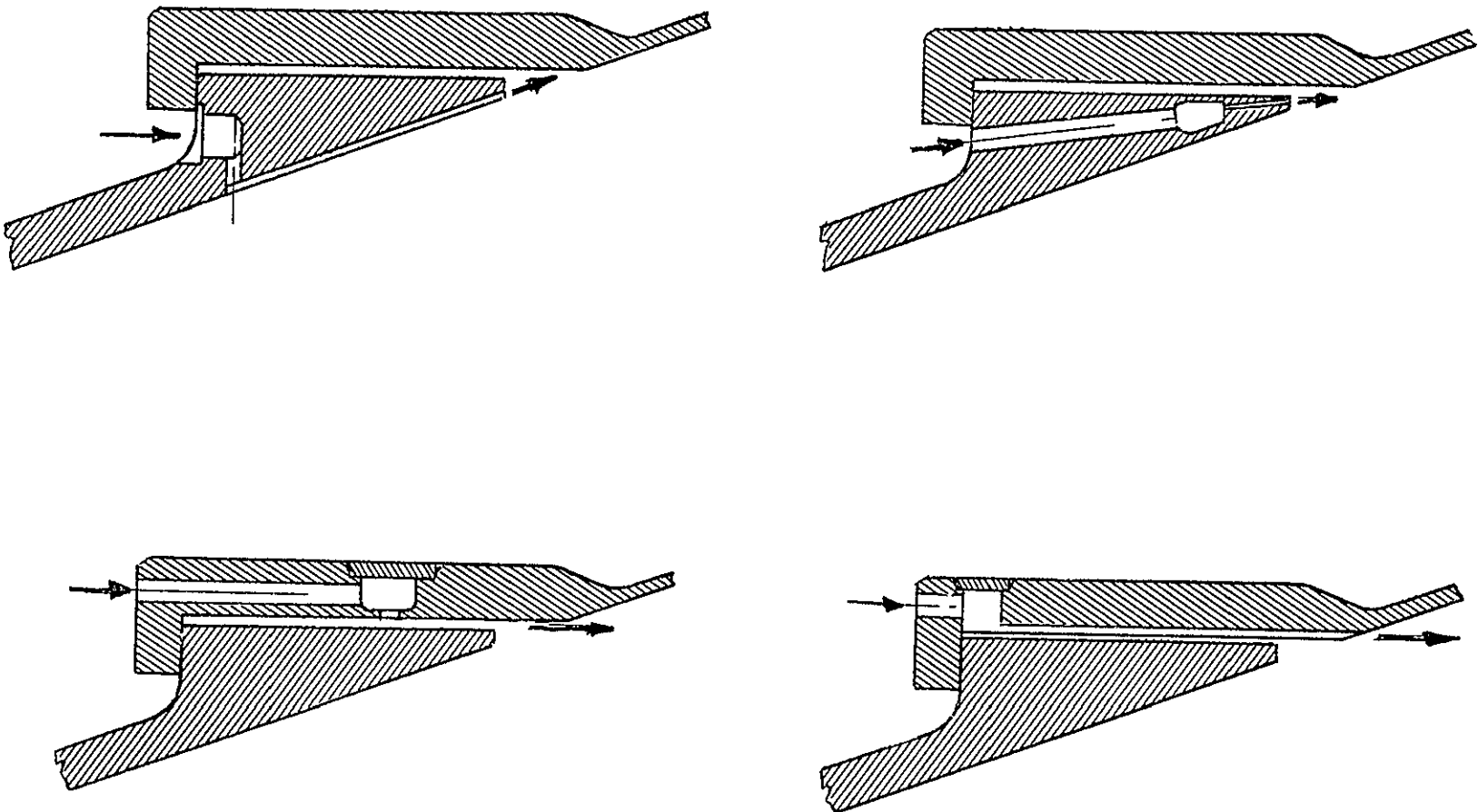
ATTACHMENT JOINT COOLING WITH SECONDARY COOLANT

Figure 4
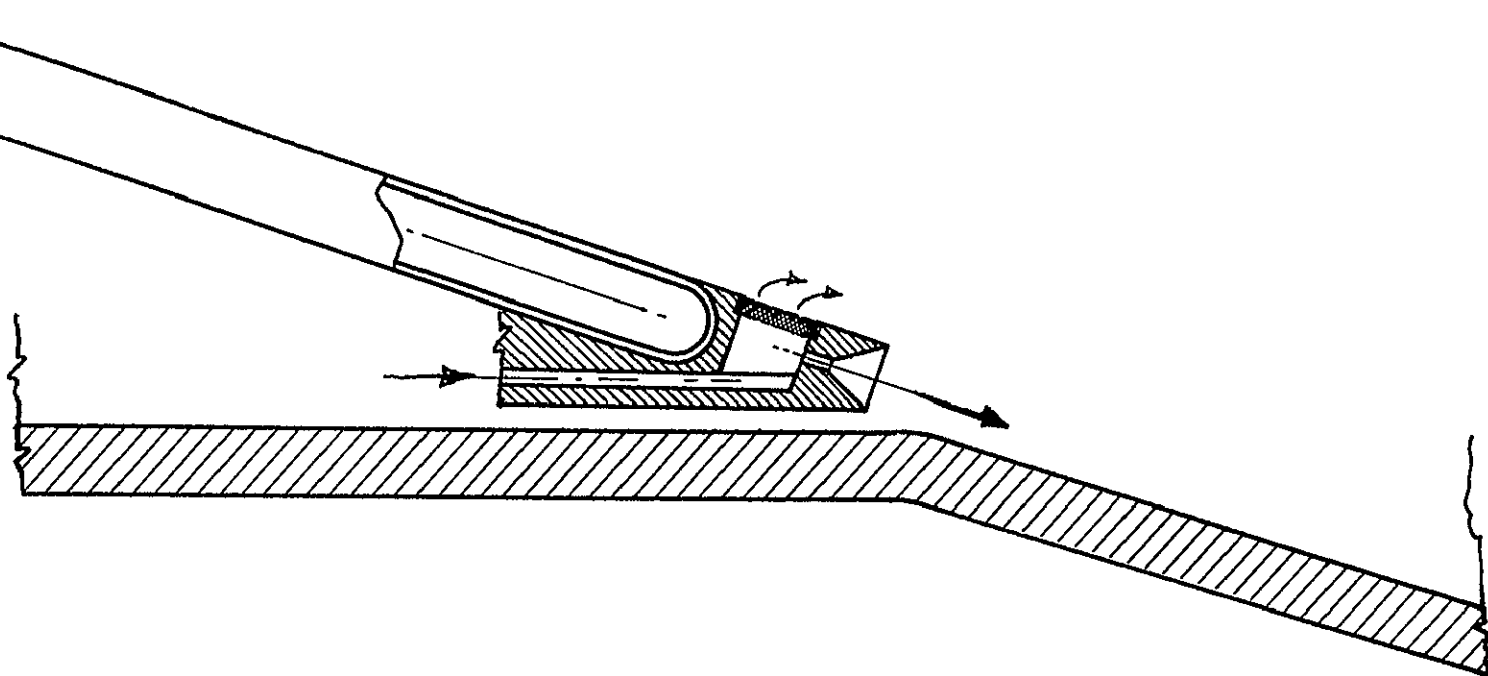
TIP COOLING BY INJECTING SECONDARY COOLANT THROUGH
RIGID MESH AND SUPERSONIC NOZZLE

Figure 5
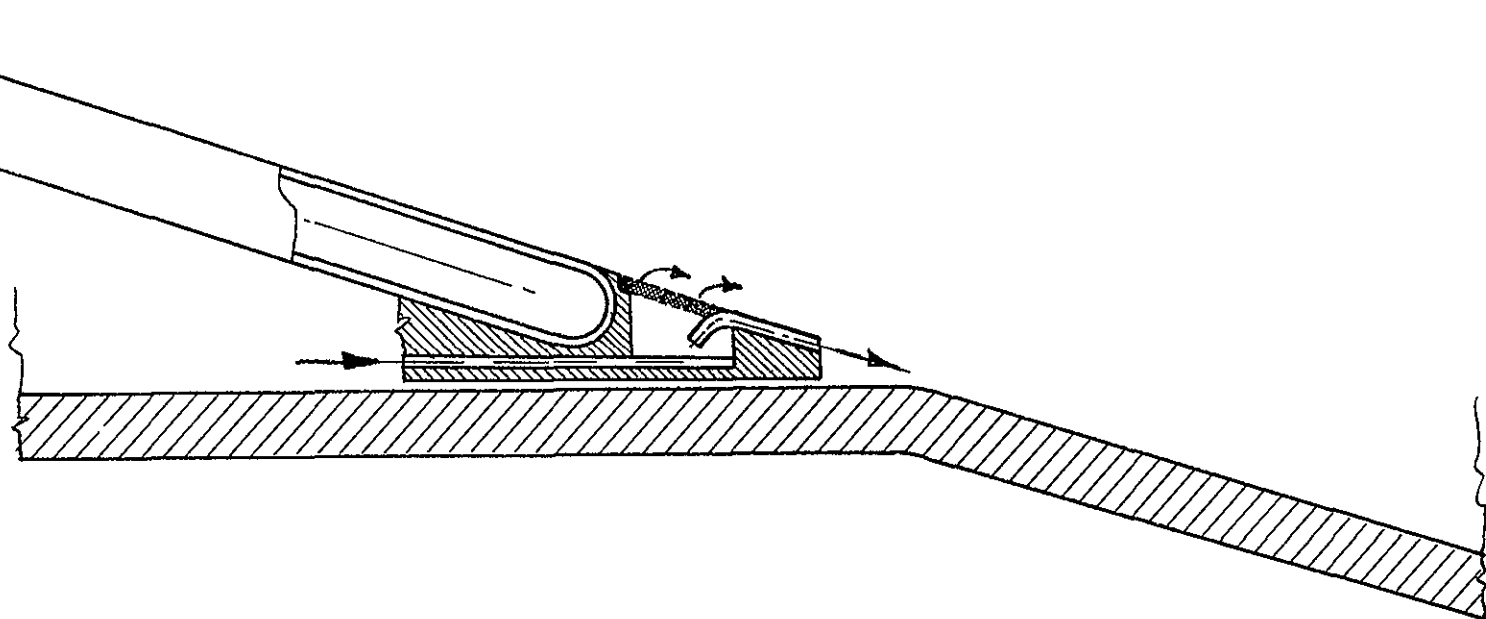
TIP COOLING BY INJECTING SECONDARY COOLANT THROUGH
RIGID MESH AND ORIENTED TUBE
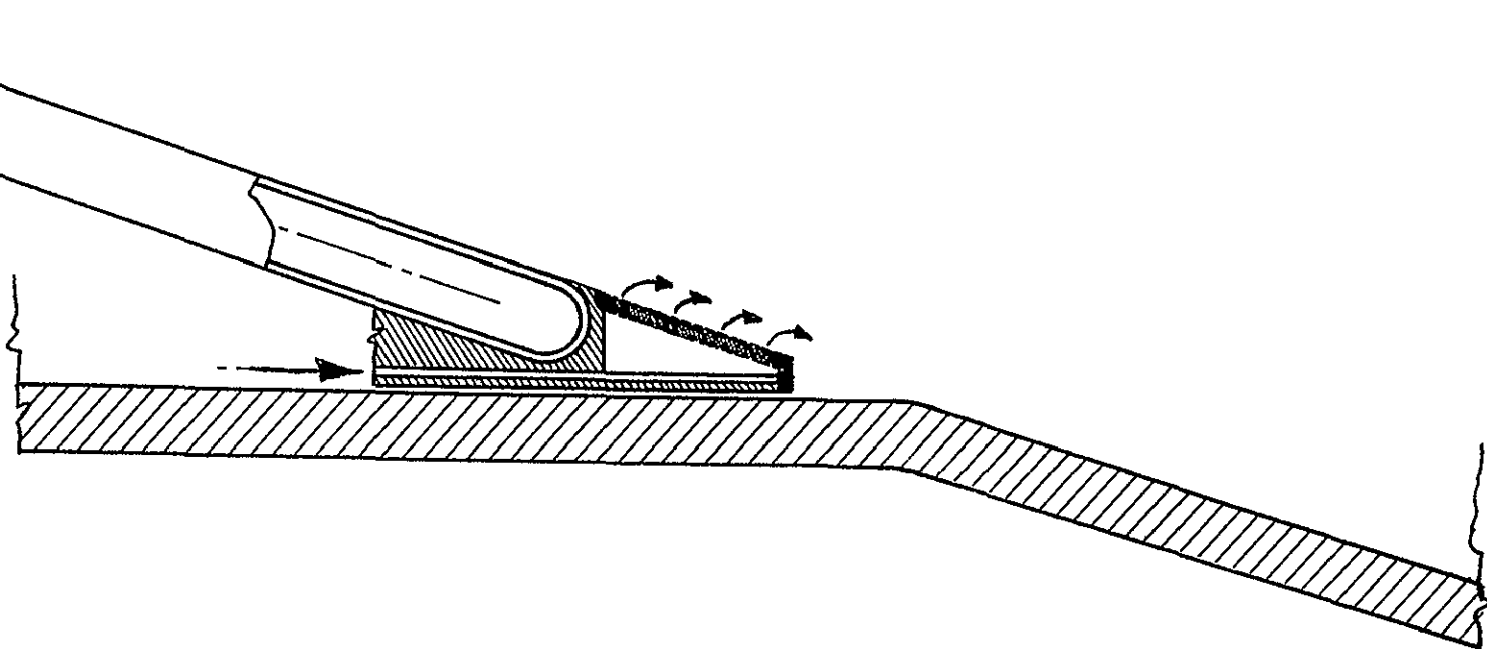
Figure 6

TIP COOLING BY INJECTING SECONDARY COOLANT THROUGH
RIGID MESH ALONE
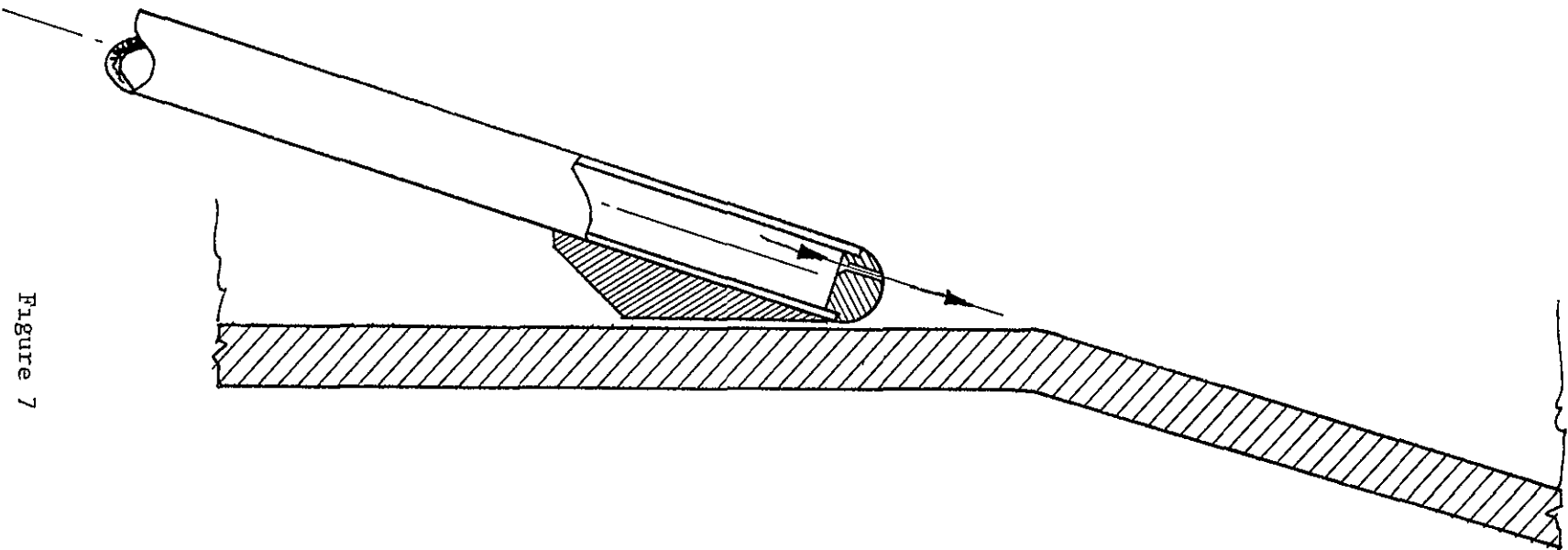
Figure 7

PROPELLANT INJECTED THROUGH SIMPLE ORIFICE
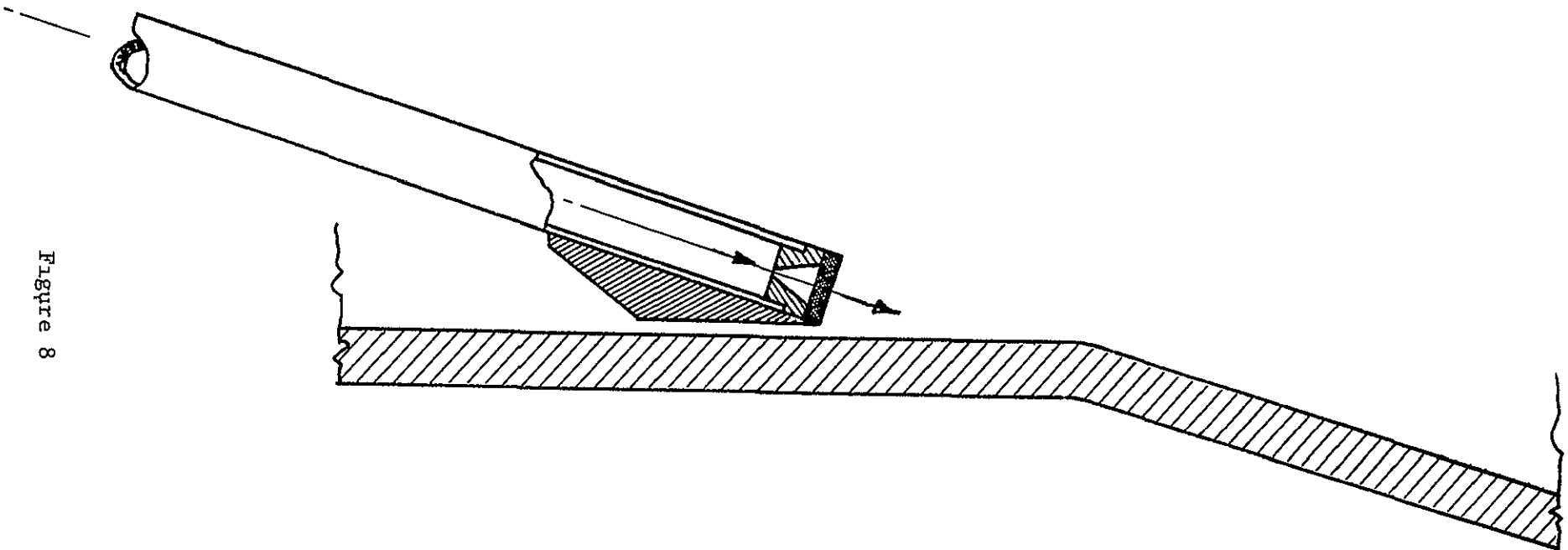
Figure 8

PROPELLANT INJECTED THROUGH RIGID MESH

Figure 9
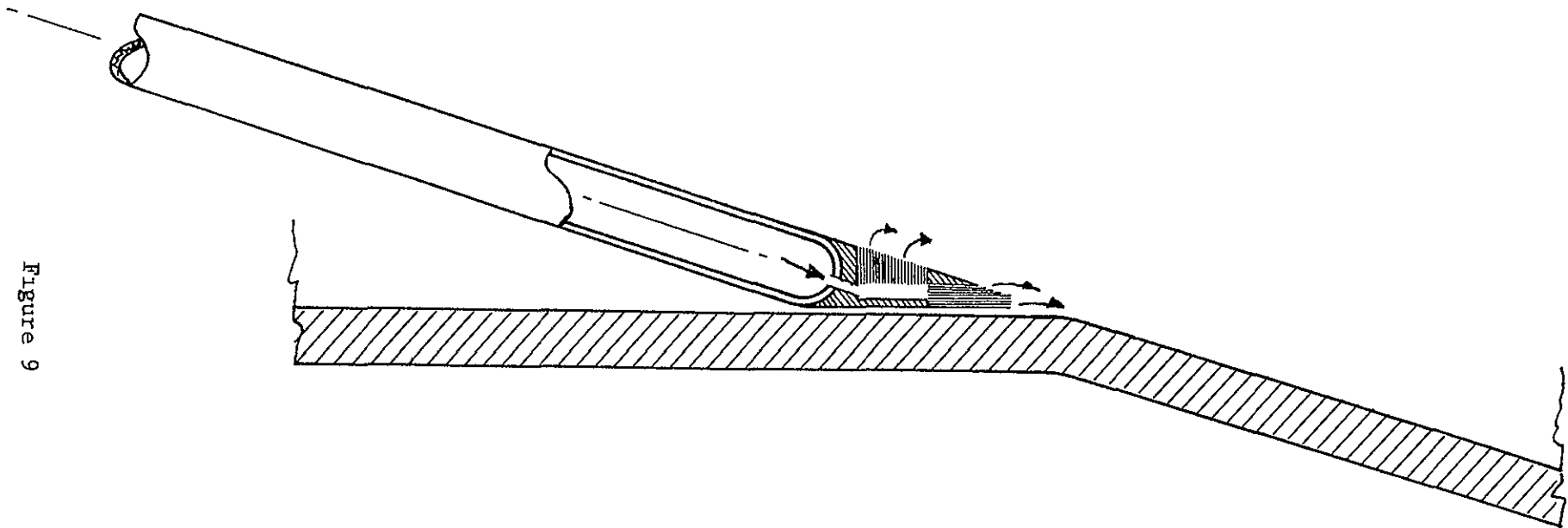
PROPELLANT INJECTED THROUGH PLATELETS

Figure 10
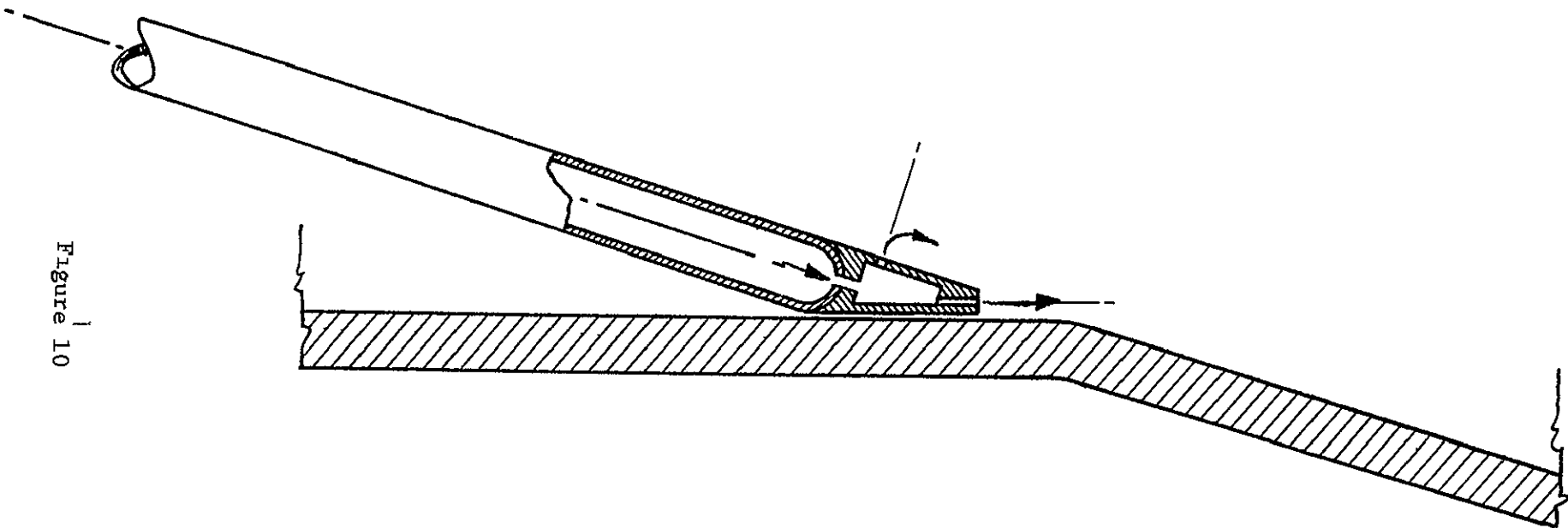
PROPELLANT INJECTED THROUGH BI-DIRECTIONAL ORIFICES

Figure 11

Extension
Being Deployed

Pressure Port

Fixed Nozzle Portion

Elastomeric Inflatable Seal
in Deflated Condition

Extension
Fully Deployed

Elastomeric Seal Inflated

INFLATABLE ELASTOMERIC SEAL CONCEPT

Pressure Port
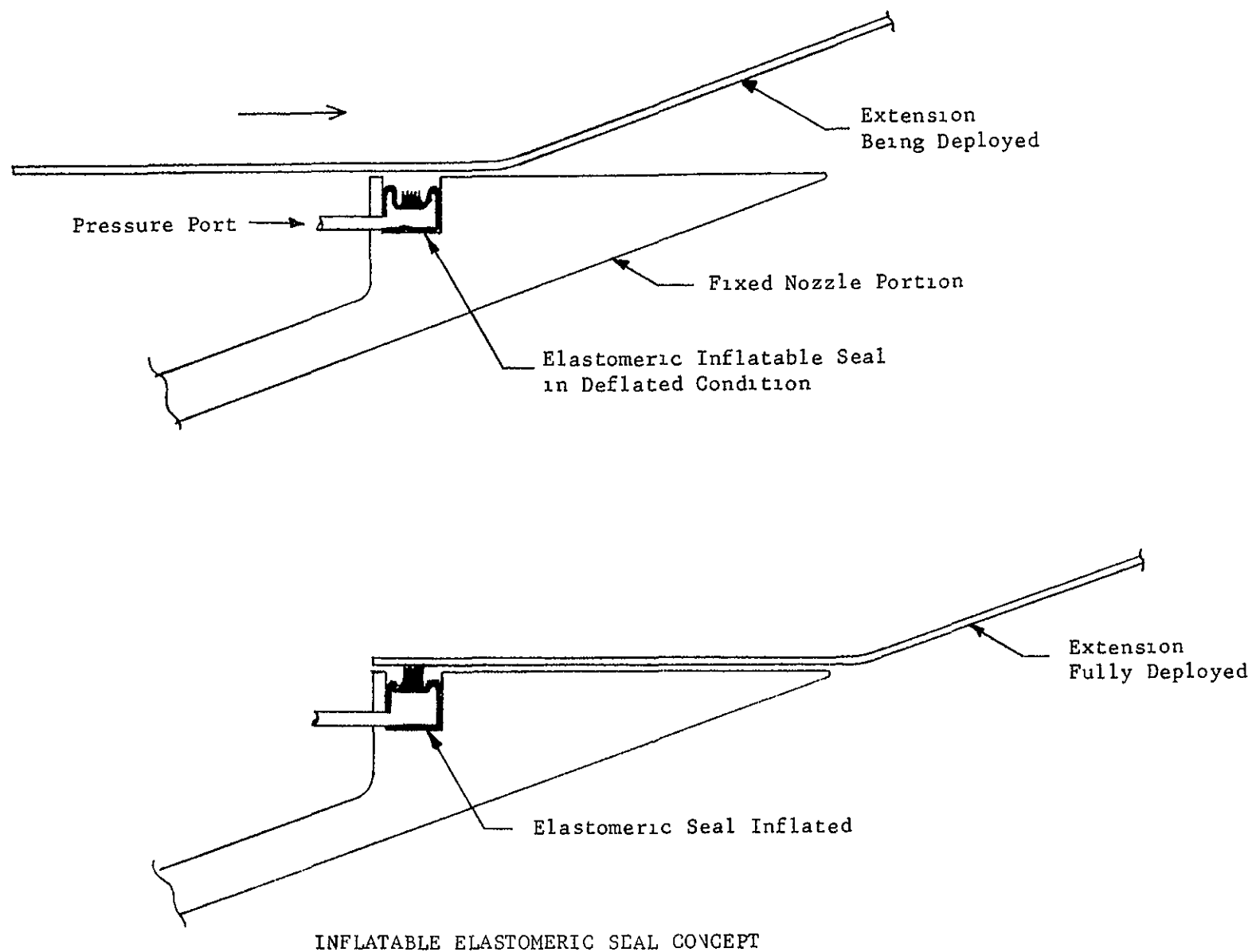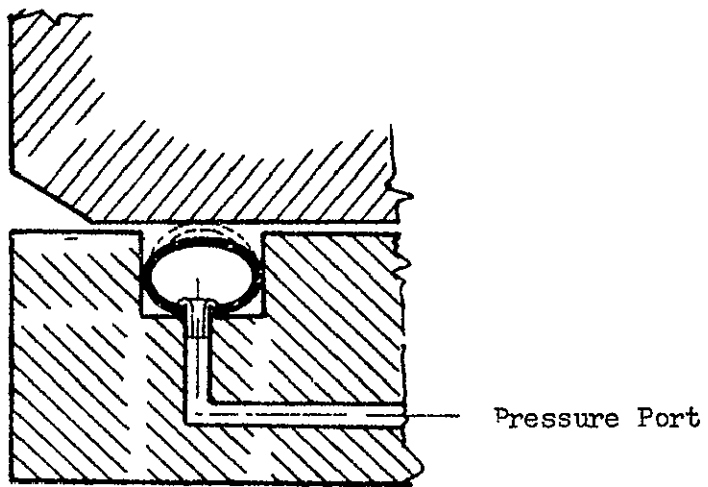
INFLATABLE METALLIC SEAL CONCEPT
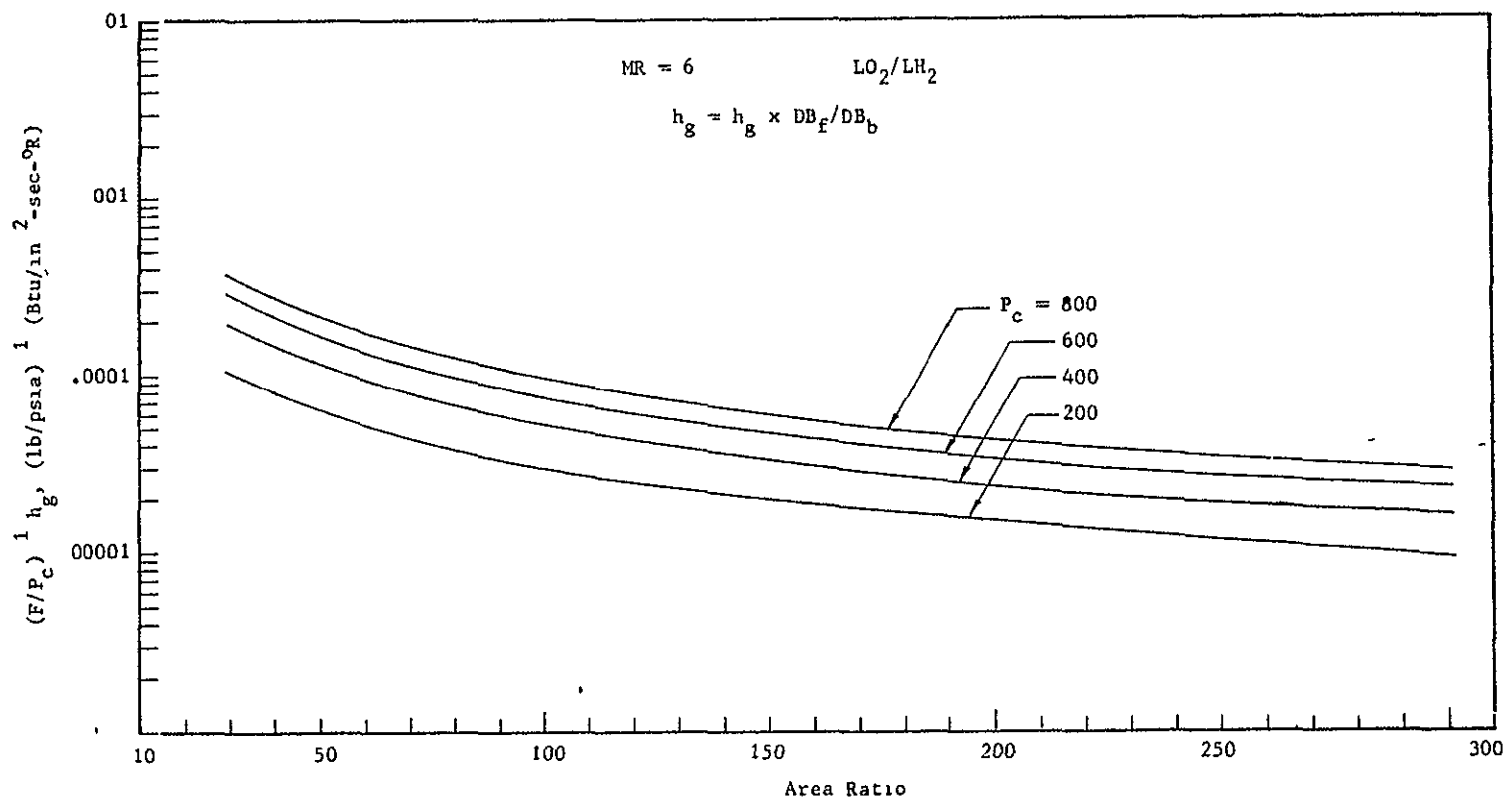
Figure 12

GAS-SIDE BULK FILM COEFFICIENT

Figure 13
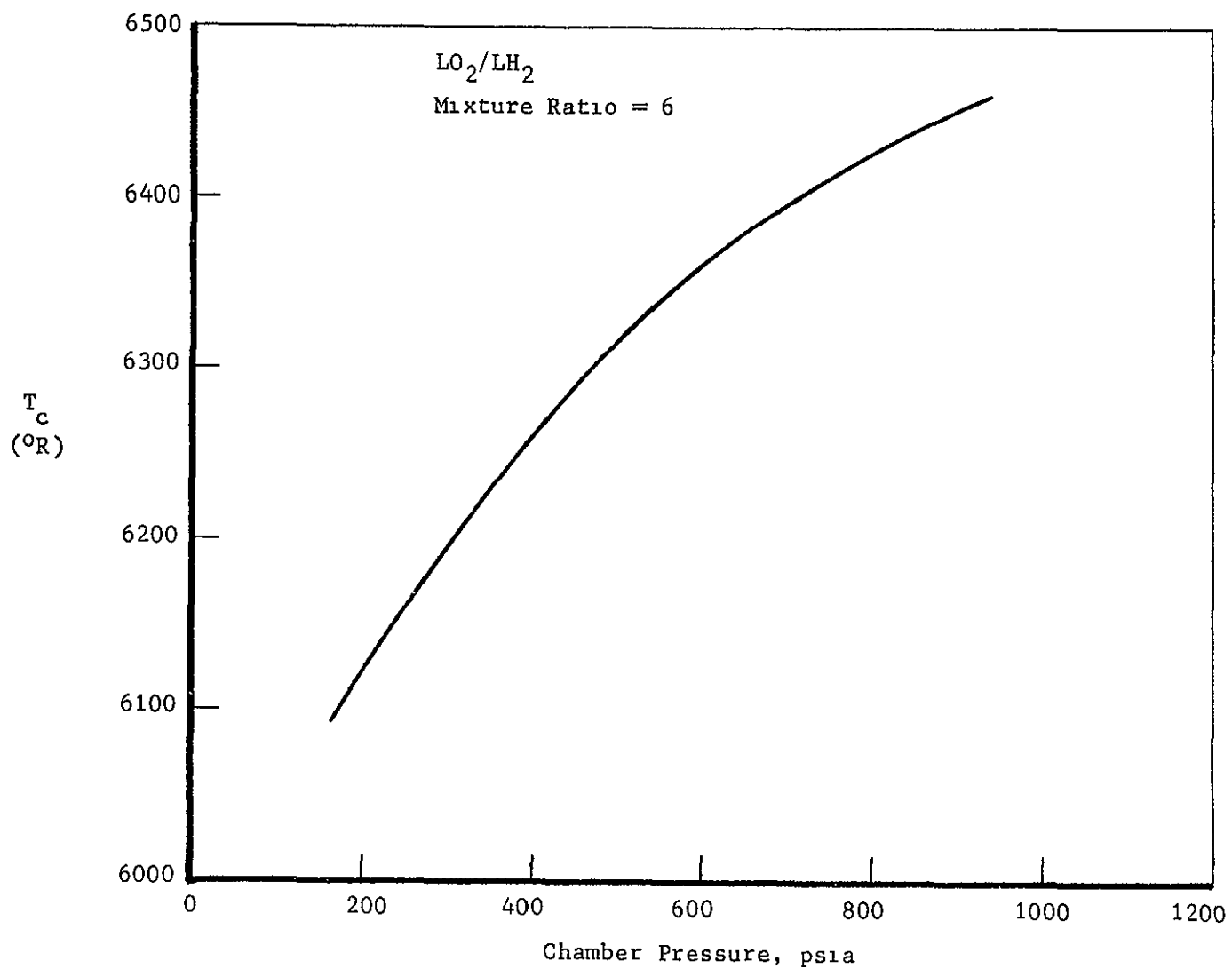
Figure 14

STAGNATION TEMPERATURE FOR O_2/H_2

$m_r = 6.0$
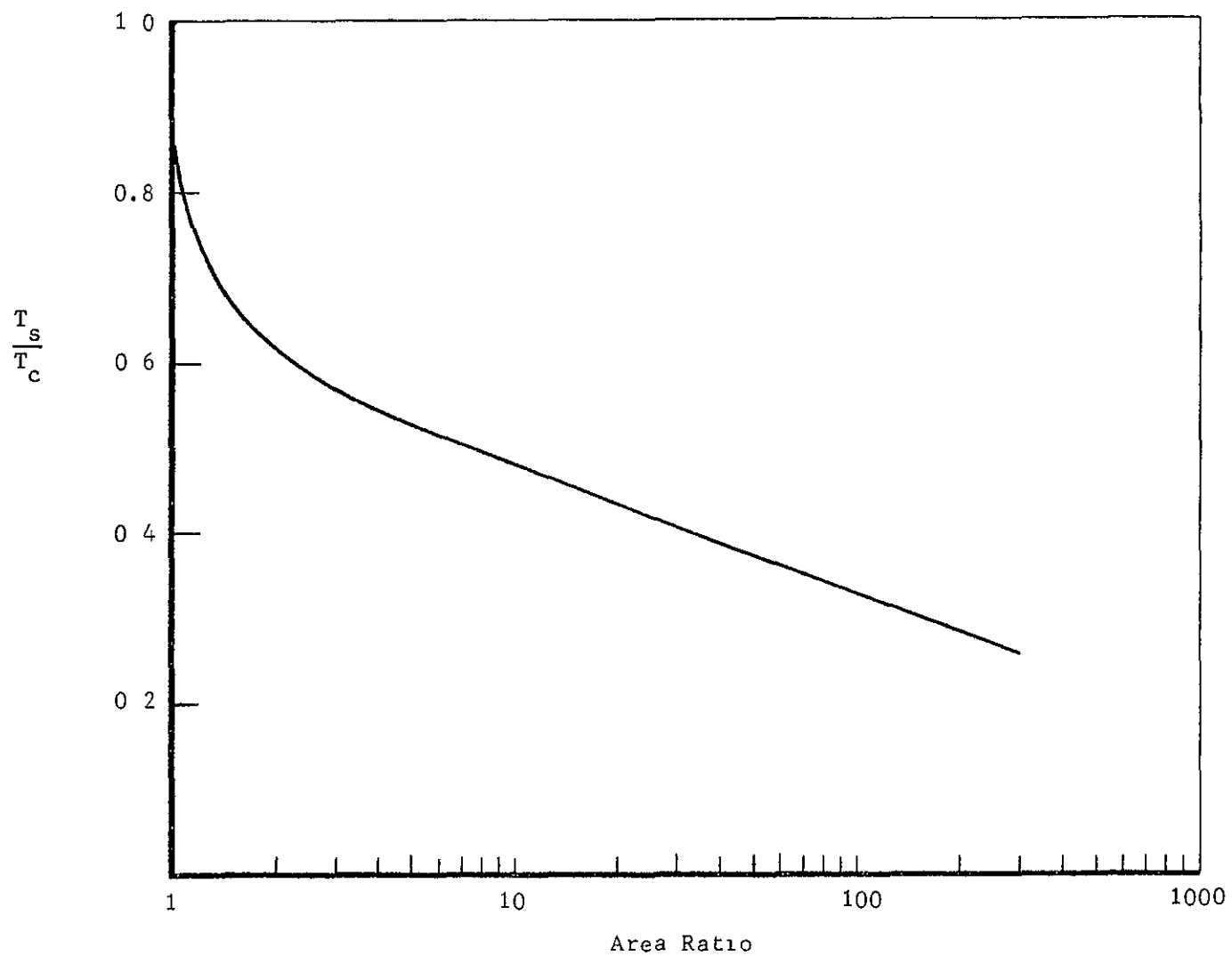
T_s/T_c vs AREA RATIO FOR O_2/H_2, MIXTURE RATIO = 6 0

Figure 15

Figure 16

$$DB = 0.026 \frac{c_{pf} \mu^{0.2}}{Pr_f^{0.6}} \left(\frac{4}{\pi} \frac{\rho}{\rho_s}\right)^{0.8}$$

LO$_2$/LH$_2$ \qquad MR = 6.00

P$_c$ = 300, 500, 800

Gas Temperature, °R

DB FACTOR FOR O$_2$/H$_2$
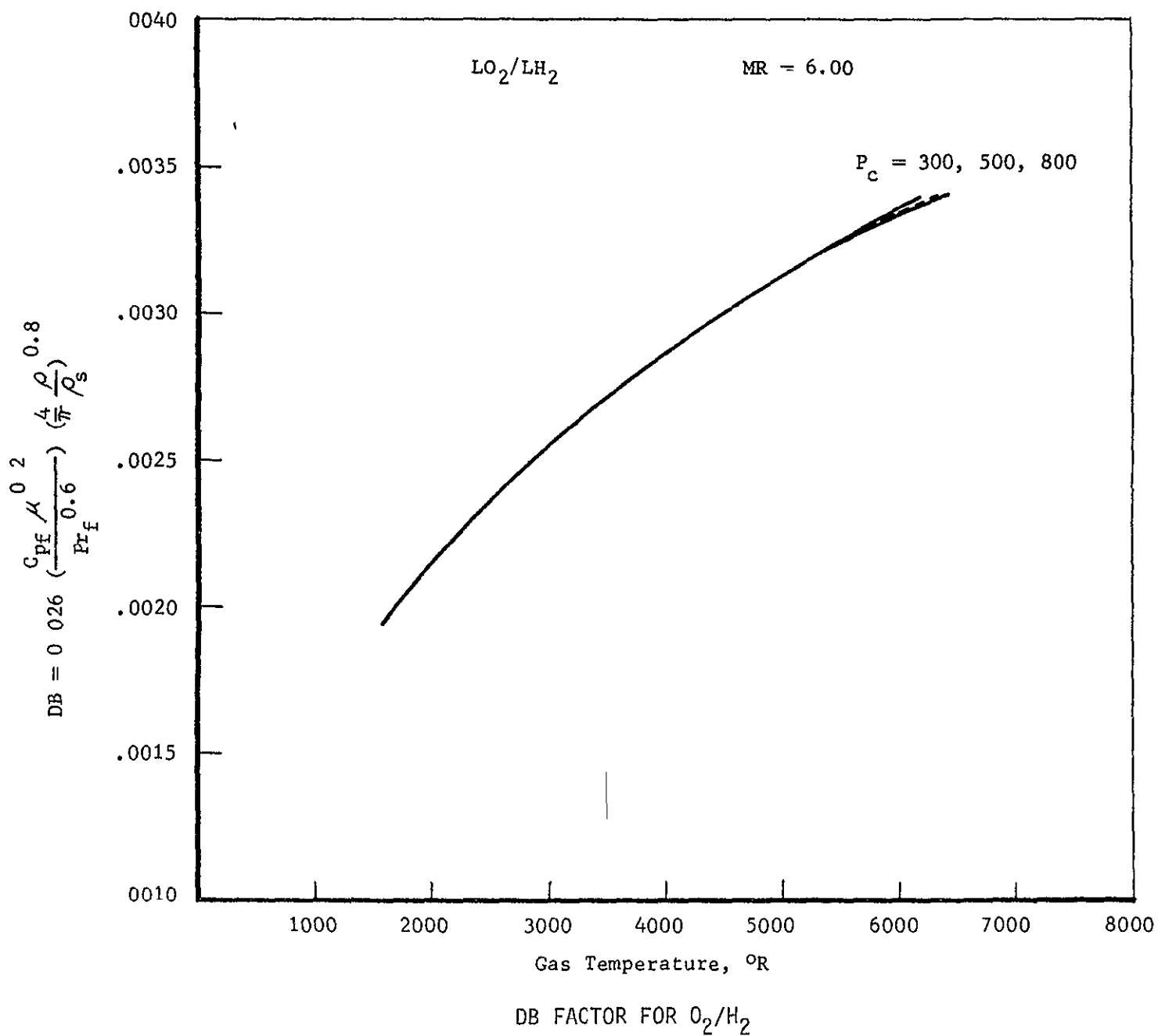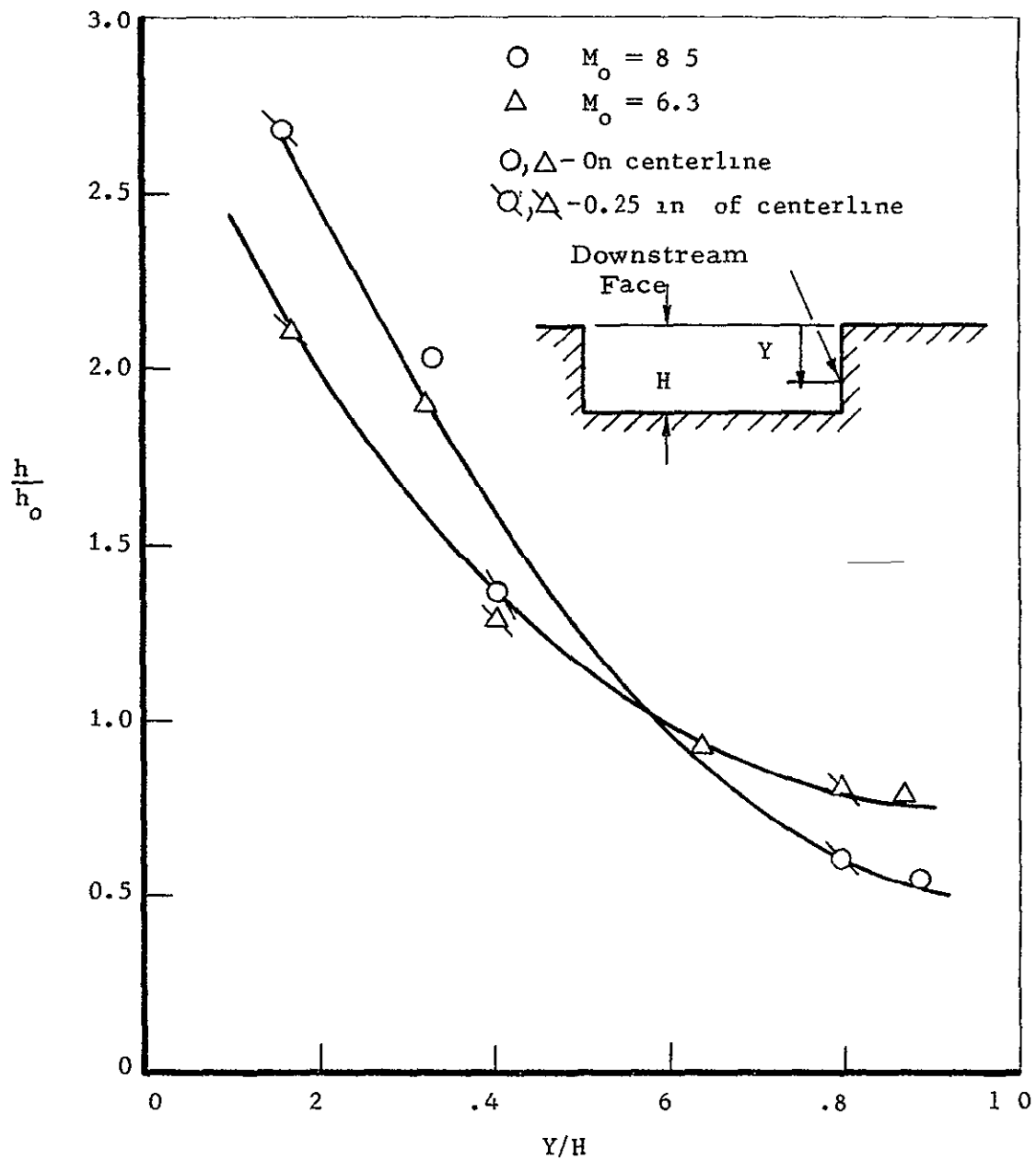
RELATIVE HEAT TRANSFER COEFFICIENT ON THE DOWNSTREAM
FACE OF A RECTANGULAR CAVITY, L/H = 5

Figure 18

Figure 17

Reattachment
Shock
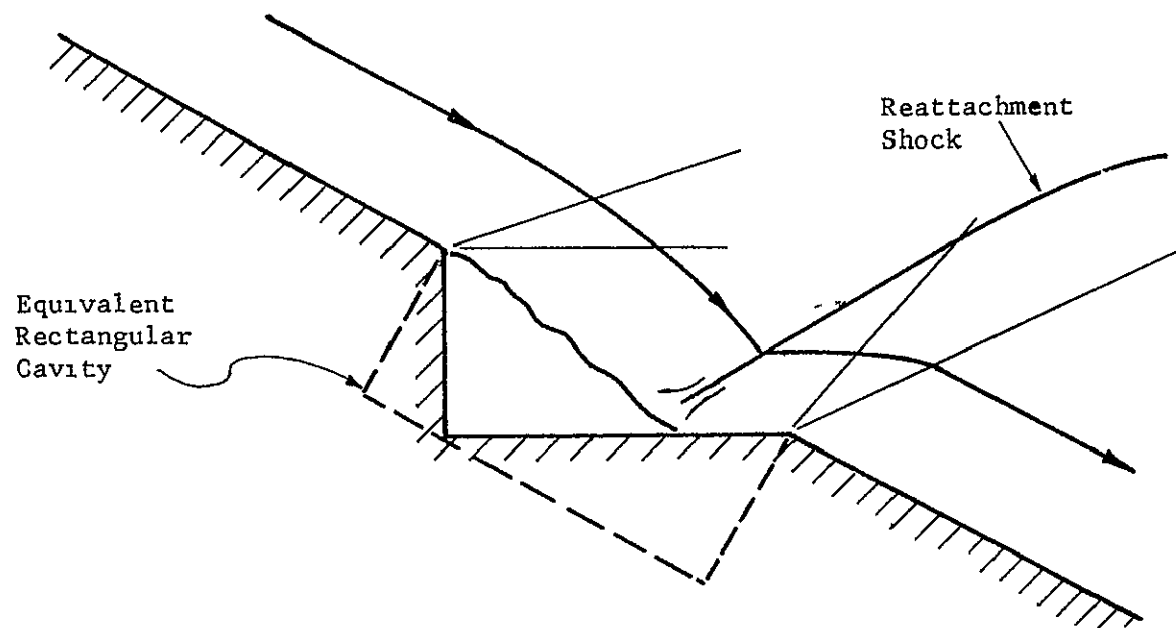
Equivalent
Rectangular
Cavity

EQUIVALENT RECTANGULAR CAVITY
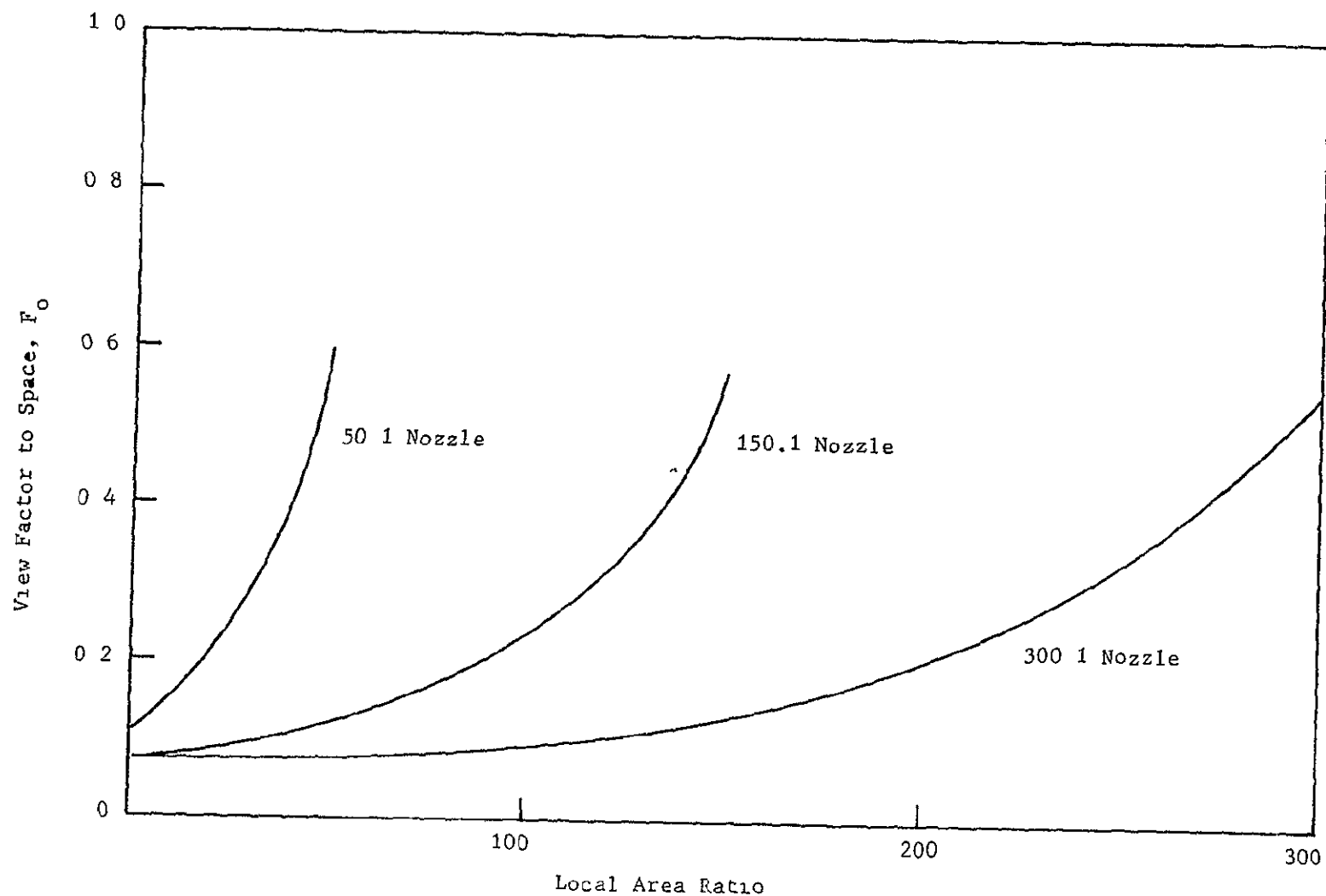
RADIATION VIEW FACTORS FROM INTERIOR NOZZLE SURFACE TO SPACE
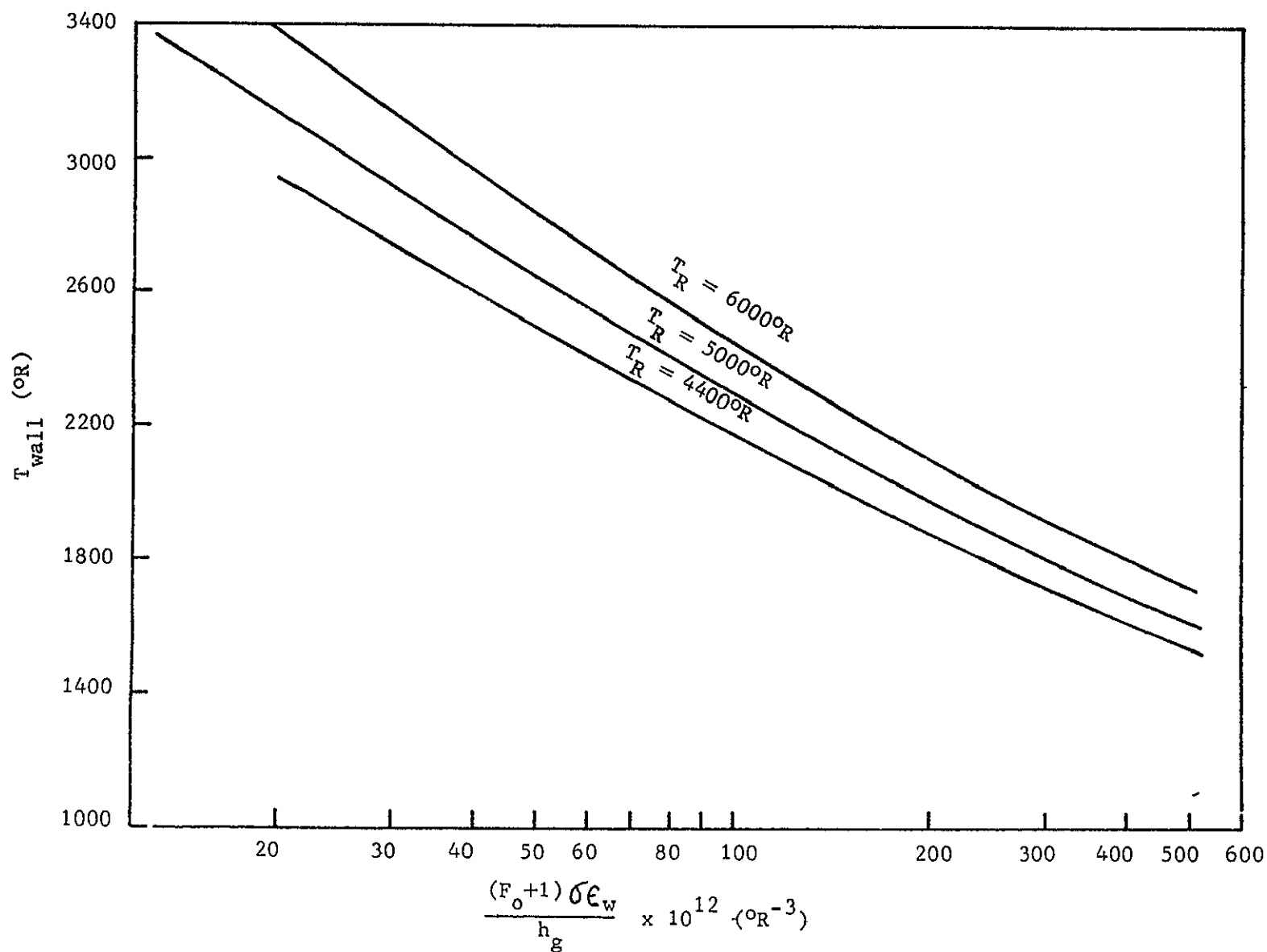
Figure 19

Figure 20

RADIATION EQUILIBRIUM TEMPERATURE FOR A THIN WALL NOZZLE
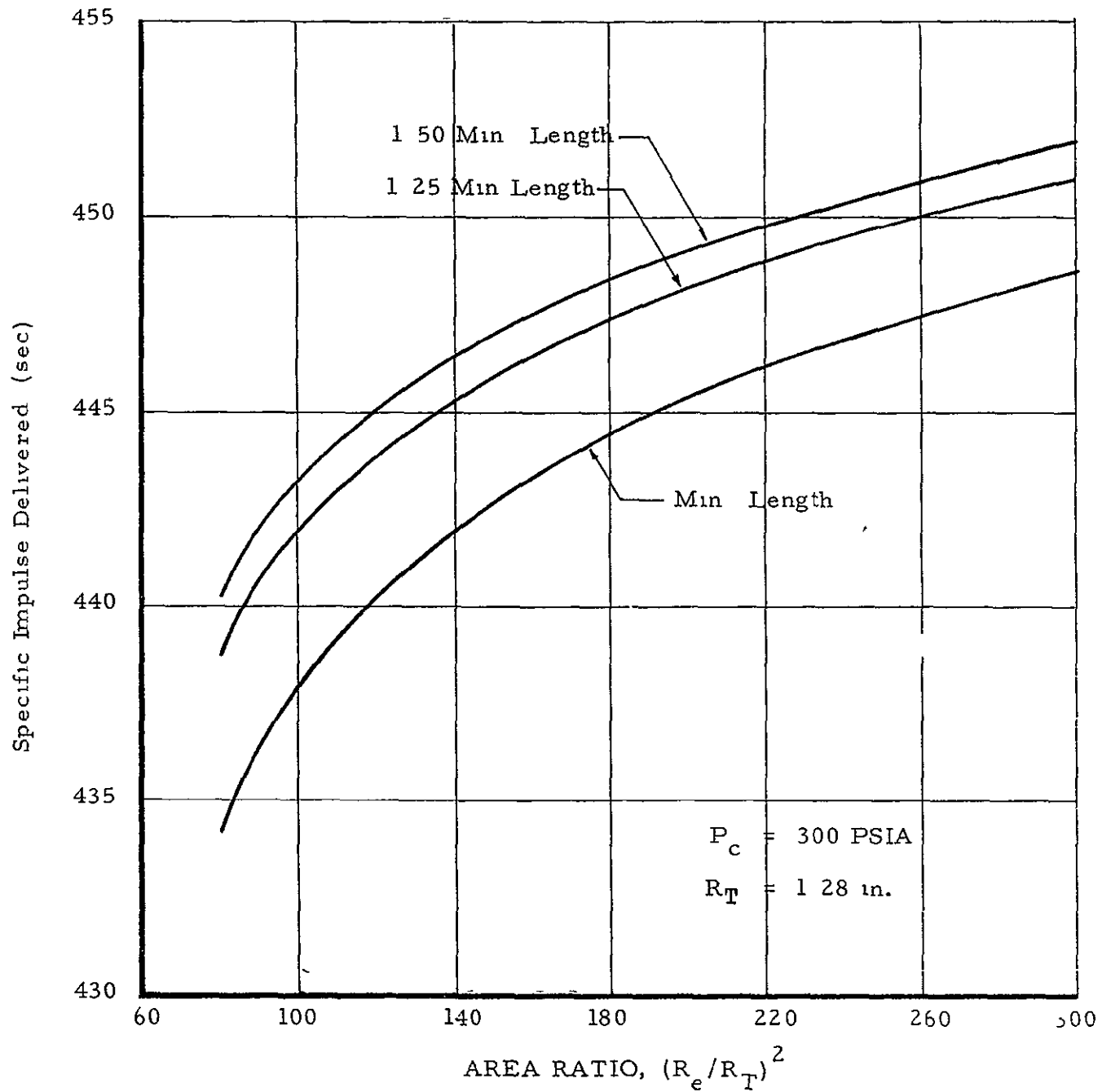
DELIVERED SPECIFIC IMPULSE VS AREA RATIO

$(R_t = 1\ 28,\ P_c = 300\ PSIA)$

Figure 21
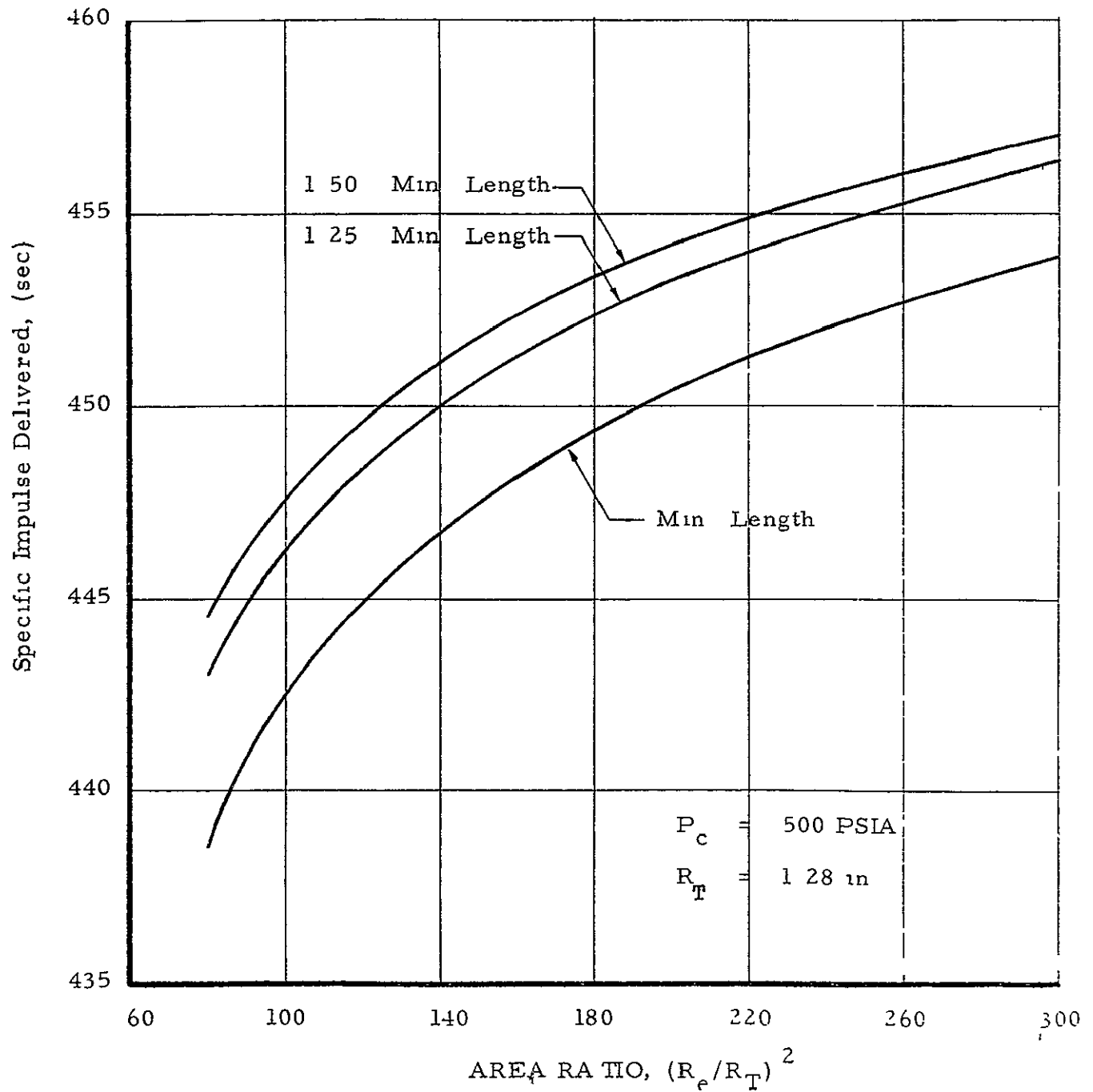
DELIVERED SPECIFIC IMPULSE VS AREA RATIO
(R_t = 1 28, P_c = 500 PSIA)

Figure 22
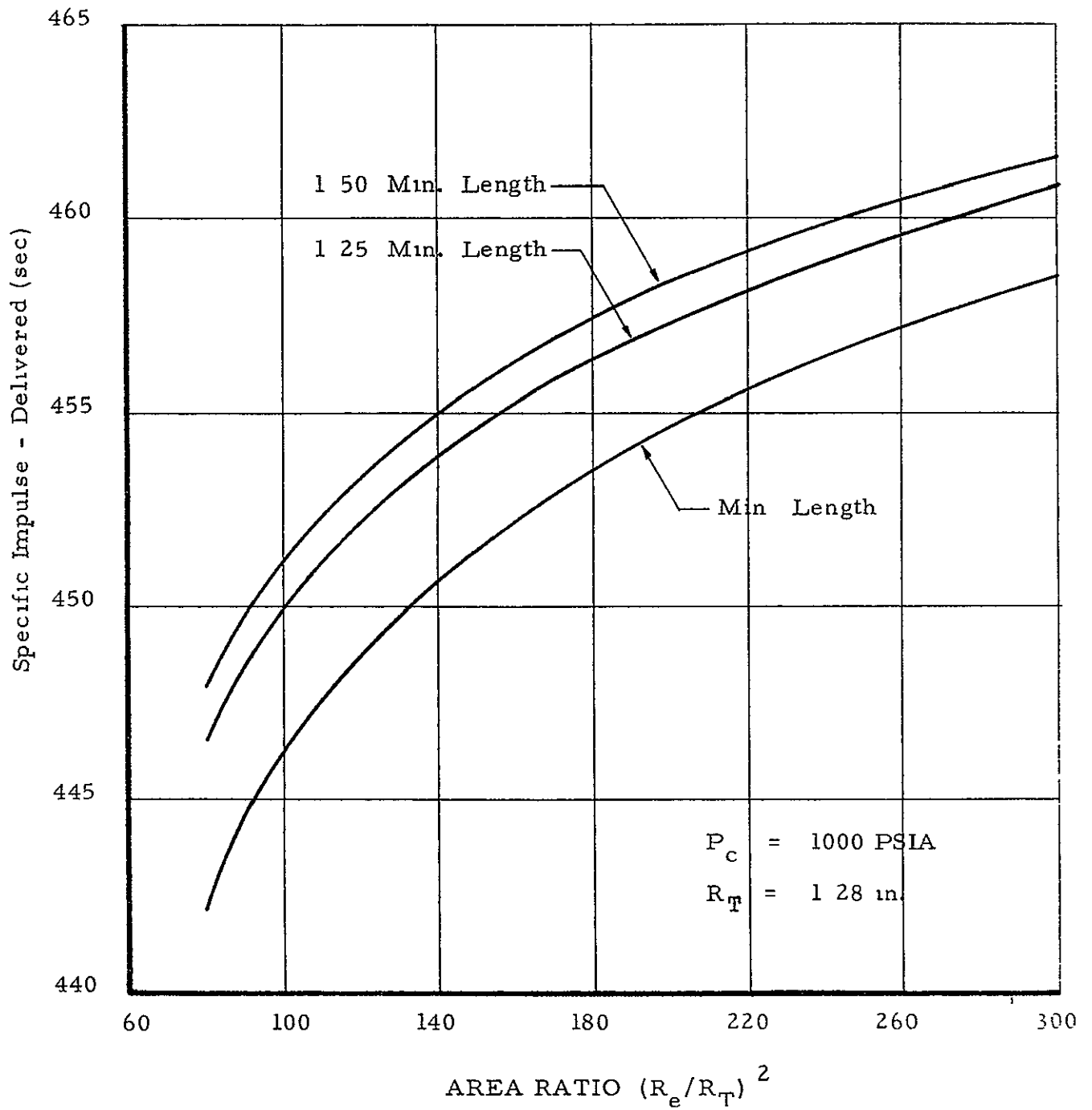
DELIVERED SPECIFIC IMPULSE VS AREA RATIO
(R_t = 1 28, P_c = 1000 PSIA)

Figure 23
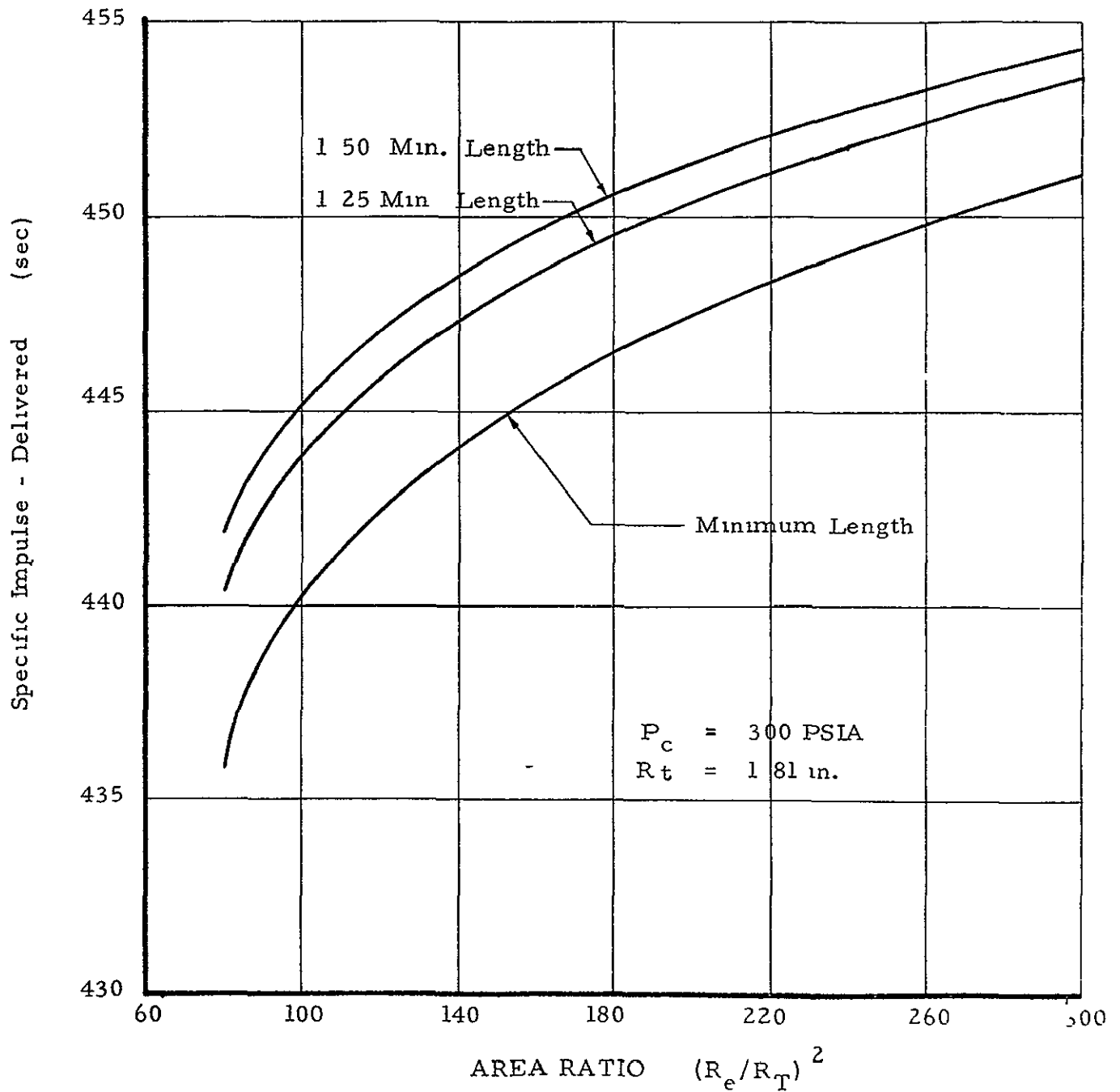
DELIVERED SPECIFIC IMPULSE VS AREA RATIO
(R_t = 1 81, P_c = 300 PSIA)

Figure 24
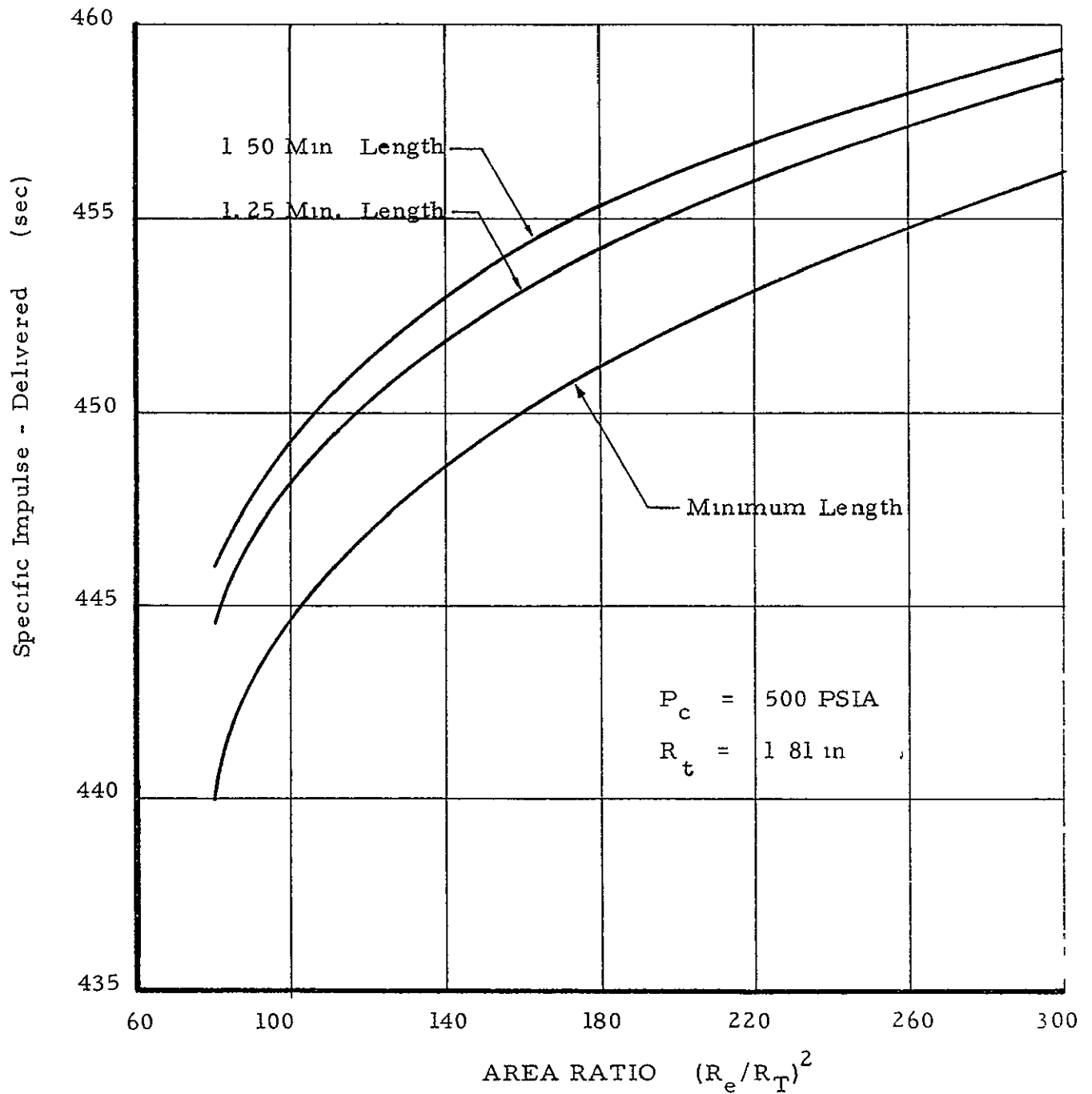
DELIVERED SPECIFIC IMPULSE VS AREA RATIO
(R_t = 1 81, P_c = 500 PSIA)

Figure 25
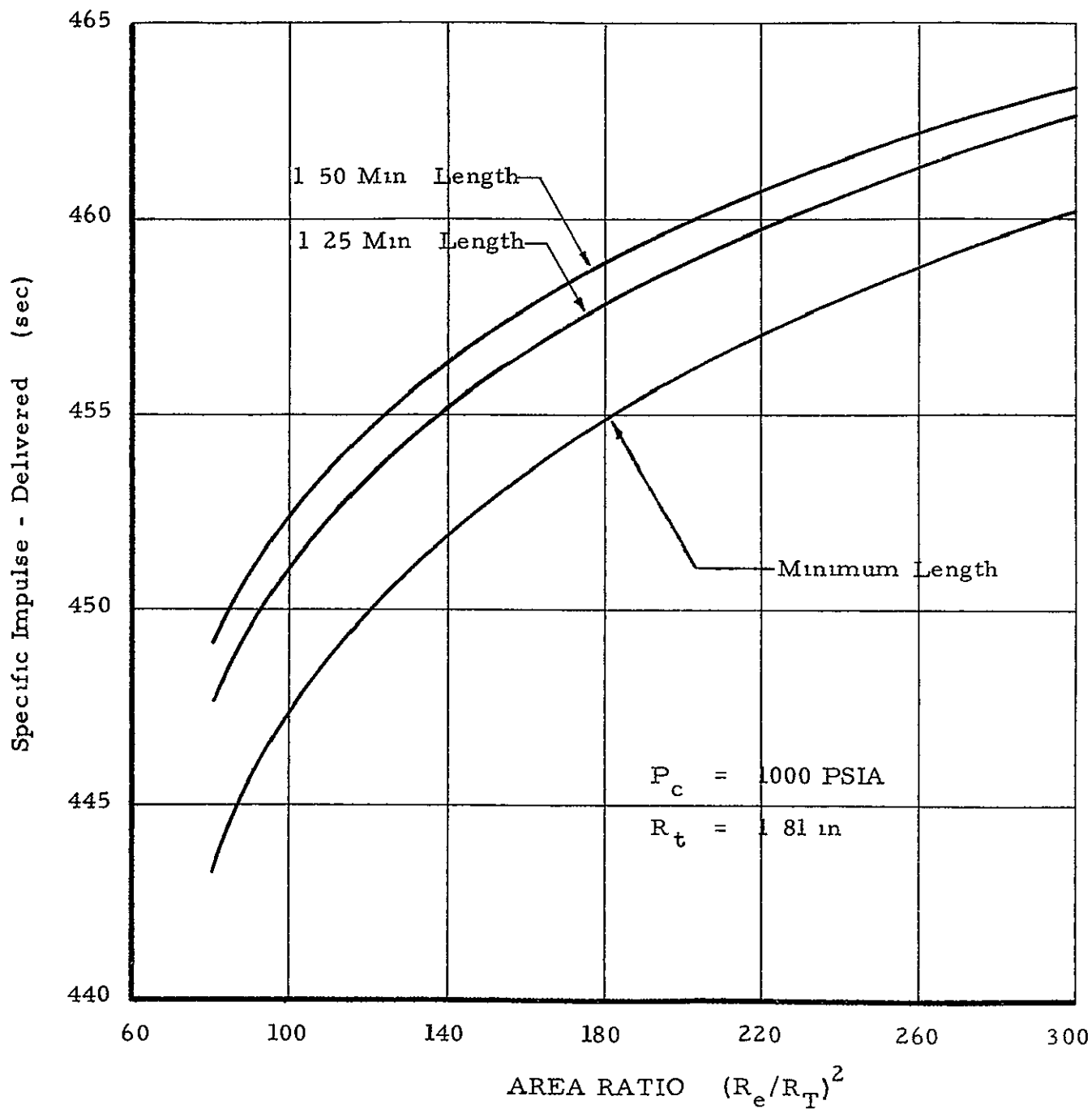
DELIVER I_{SP} VS AREA RATIO
(P_C = 1000 psia, R_t = 1 81 IN)

Figure 26
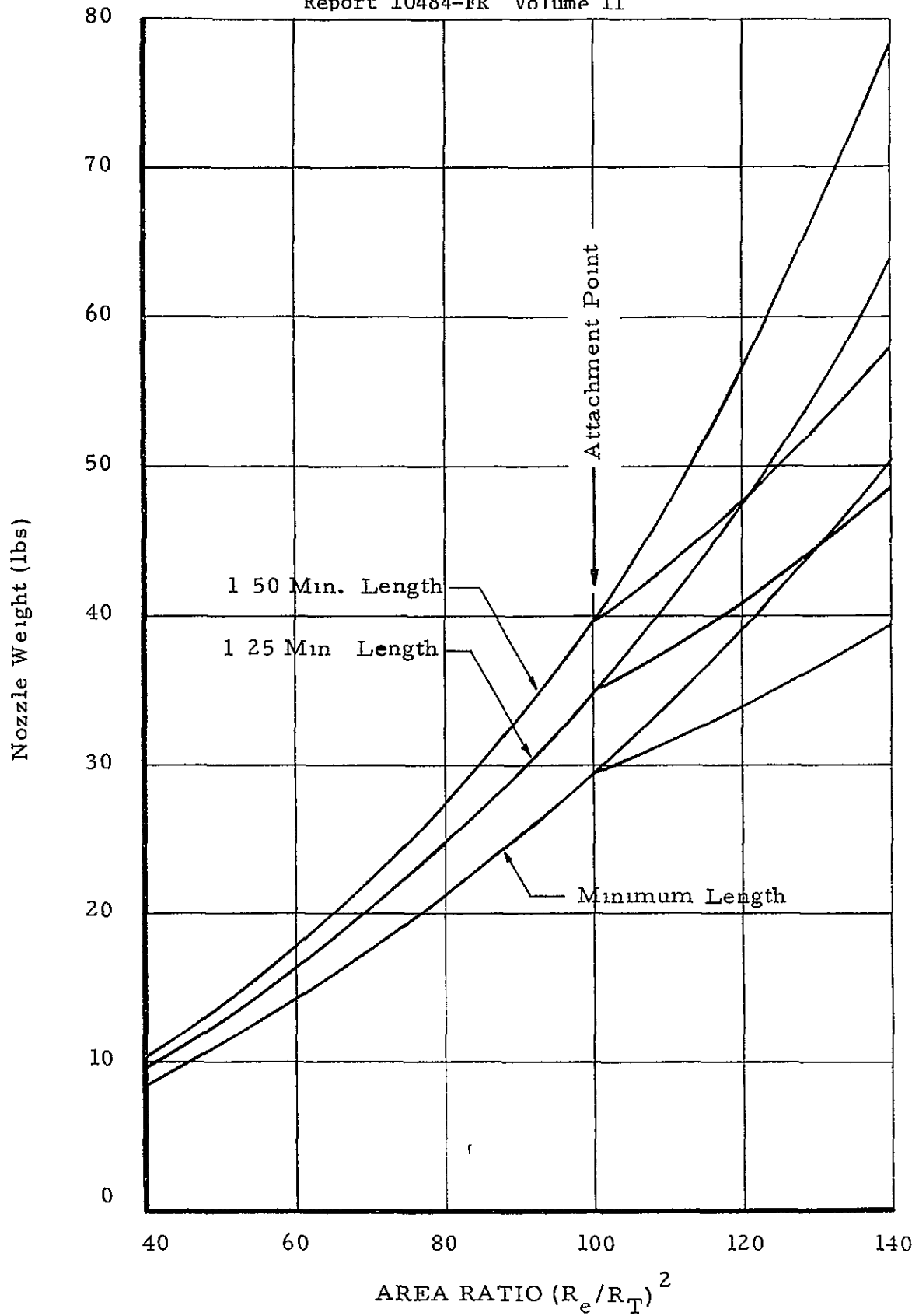
NOZZLE WEIGHT VS AREA RATIO
(RADIATION-FILM COOLED EXTENSION, EXIT AREA RATIO = 140)

Figure 27
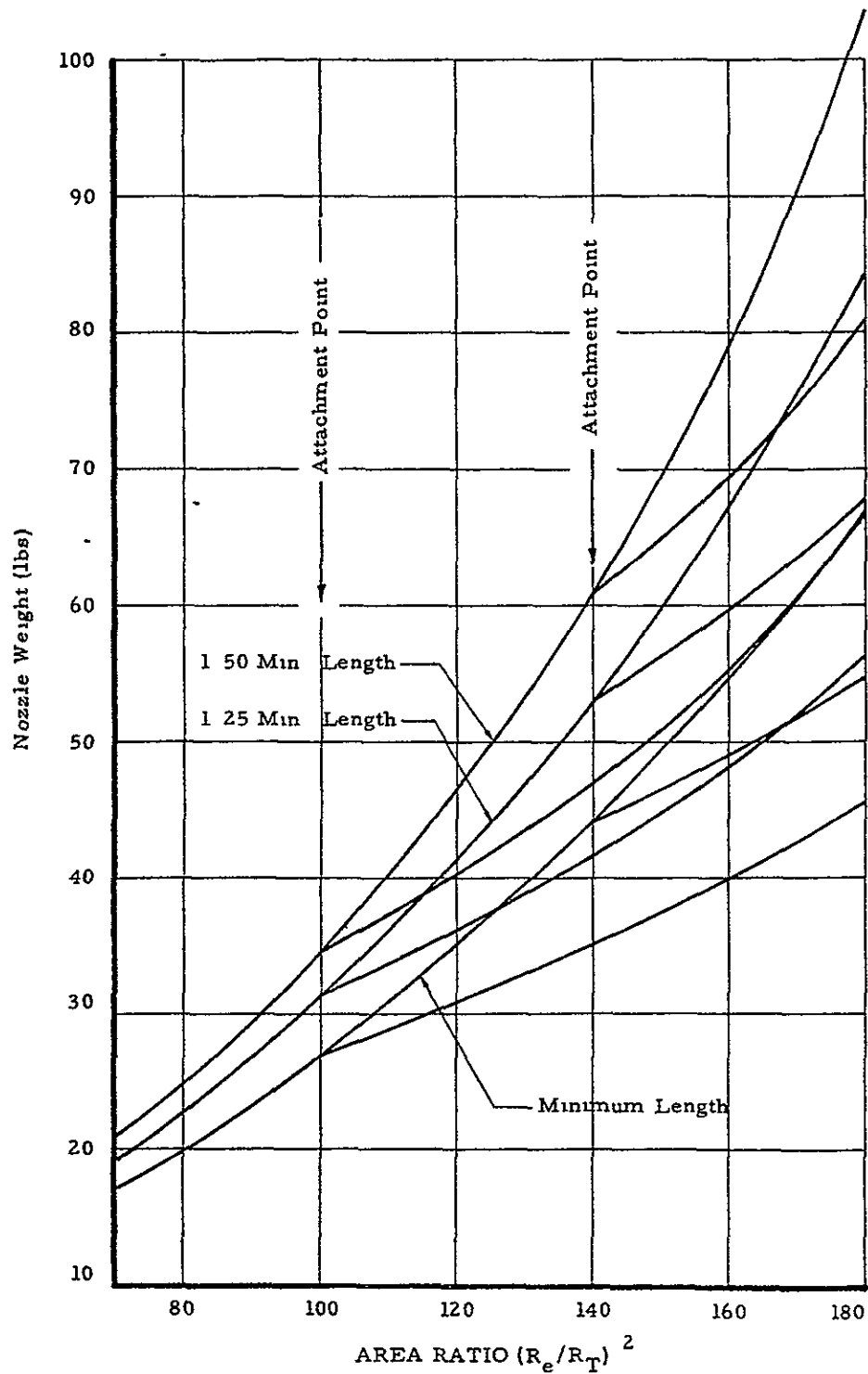
NOZZLE WEIGHT VS AREA RATIO
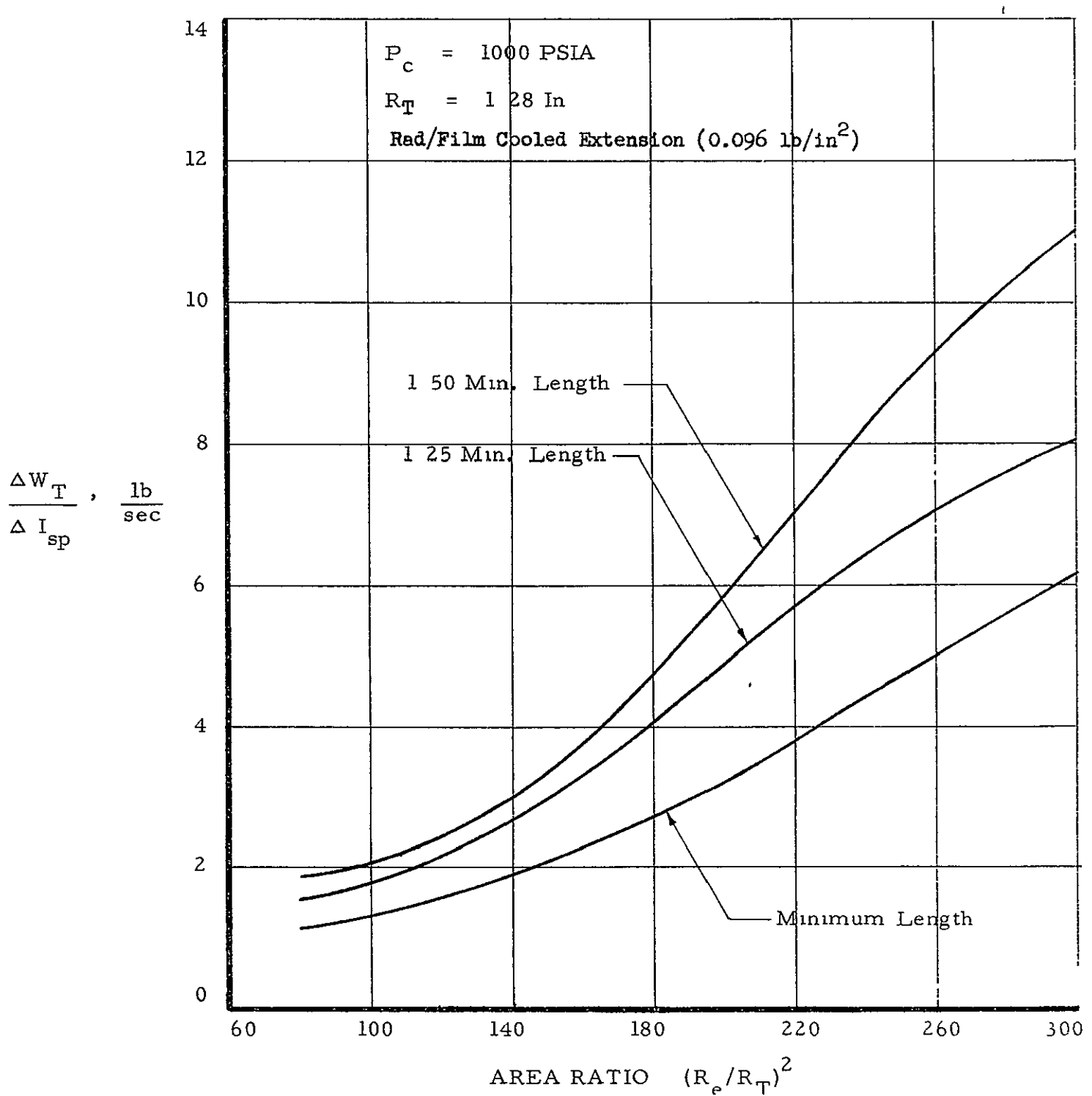(RADIATION/FILM COOLED EXTENSION, EXIT AREA RATIO = 180)

Figure 28
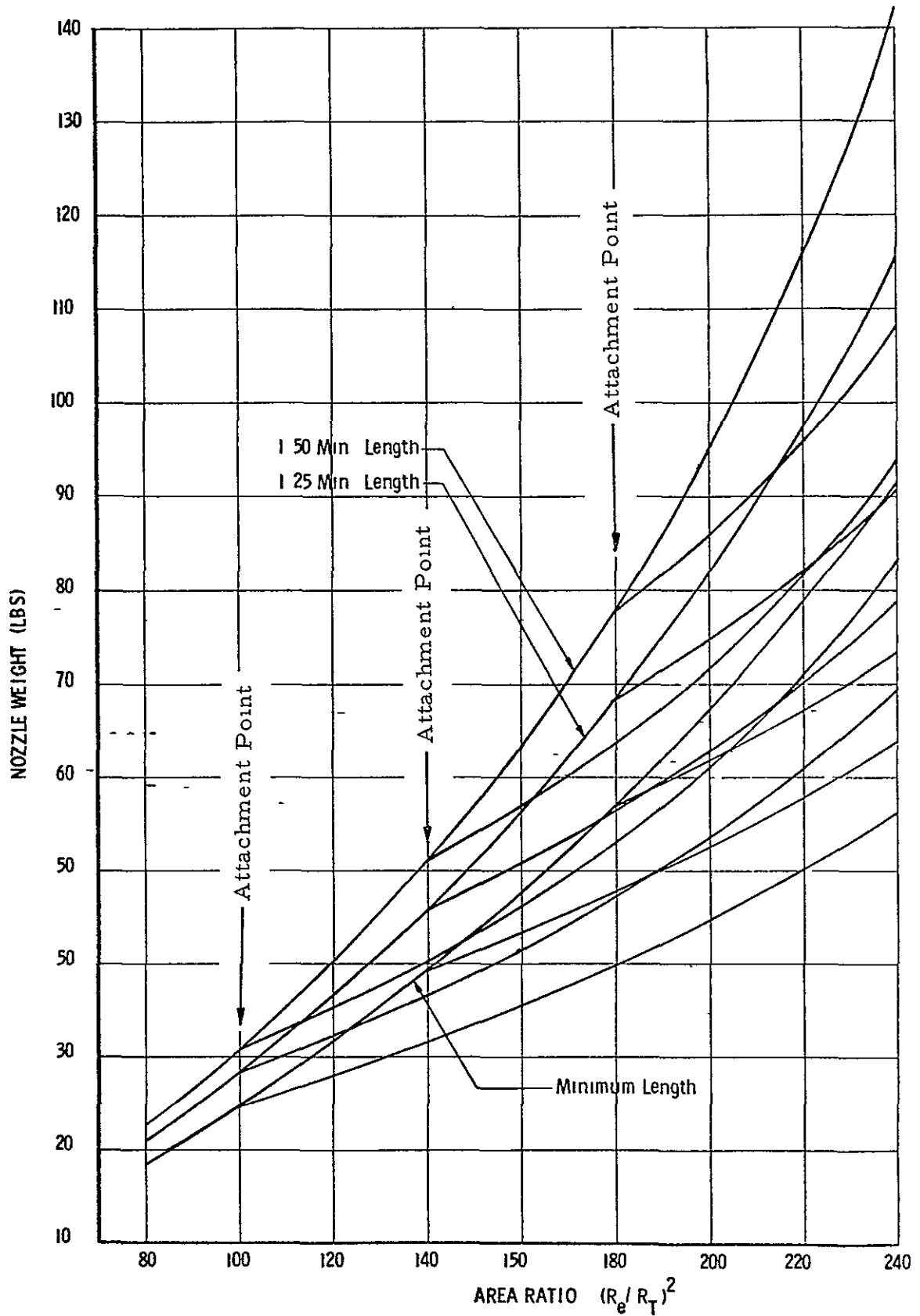
NOZZLE WEIGHT VS AREA RATIO
(RADIATION FILM COOLED EXTENSION, EXIT AREA RATIO = 240)

Figure 29
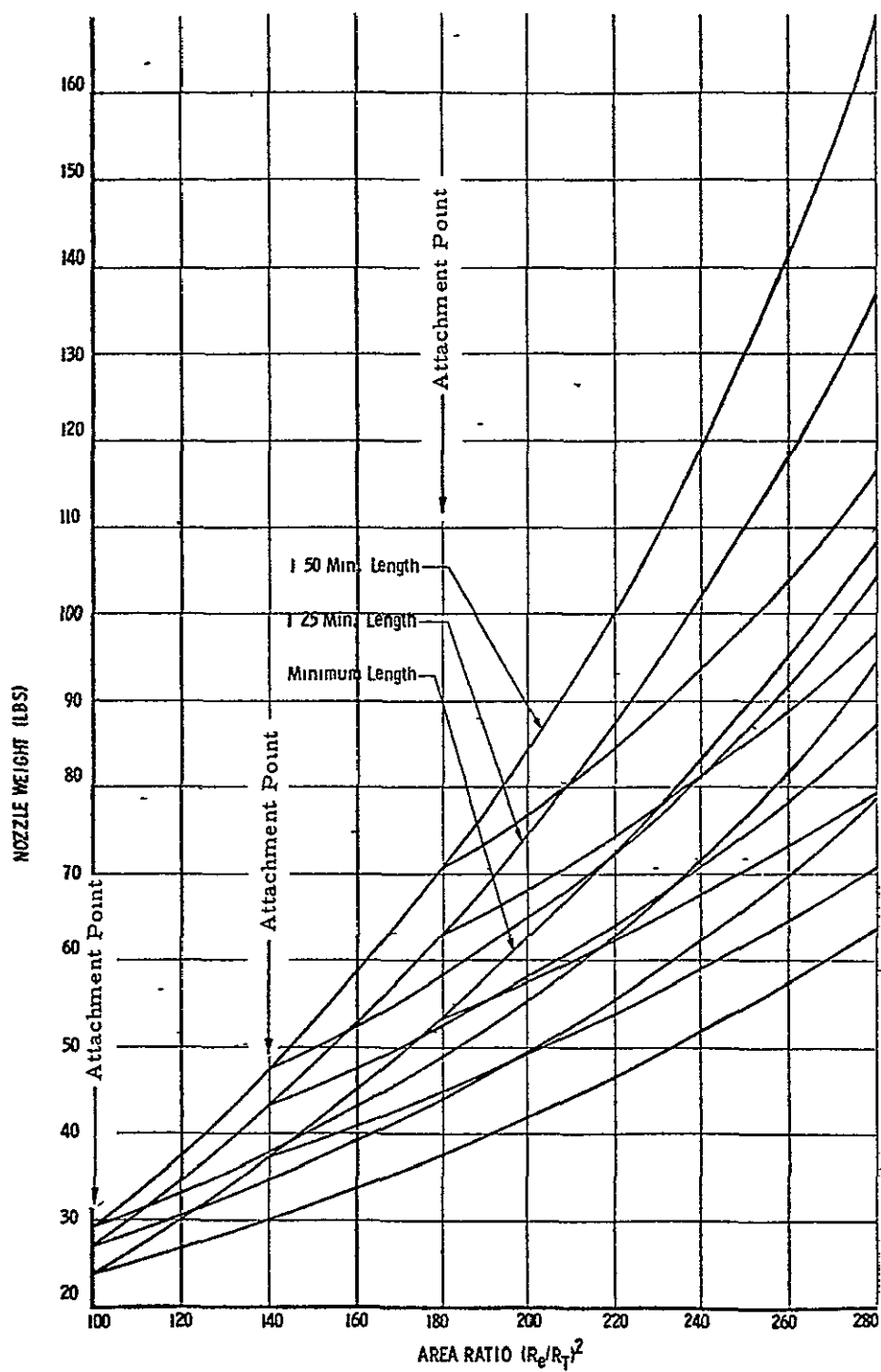
NOZZLE WEIGHT VS AREA RATIO
(RADIATION/FILM COOLED EXTENSION, EXIT AREA RATIO = 280)

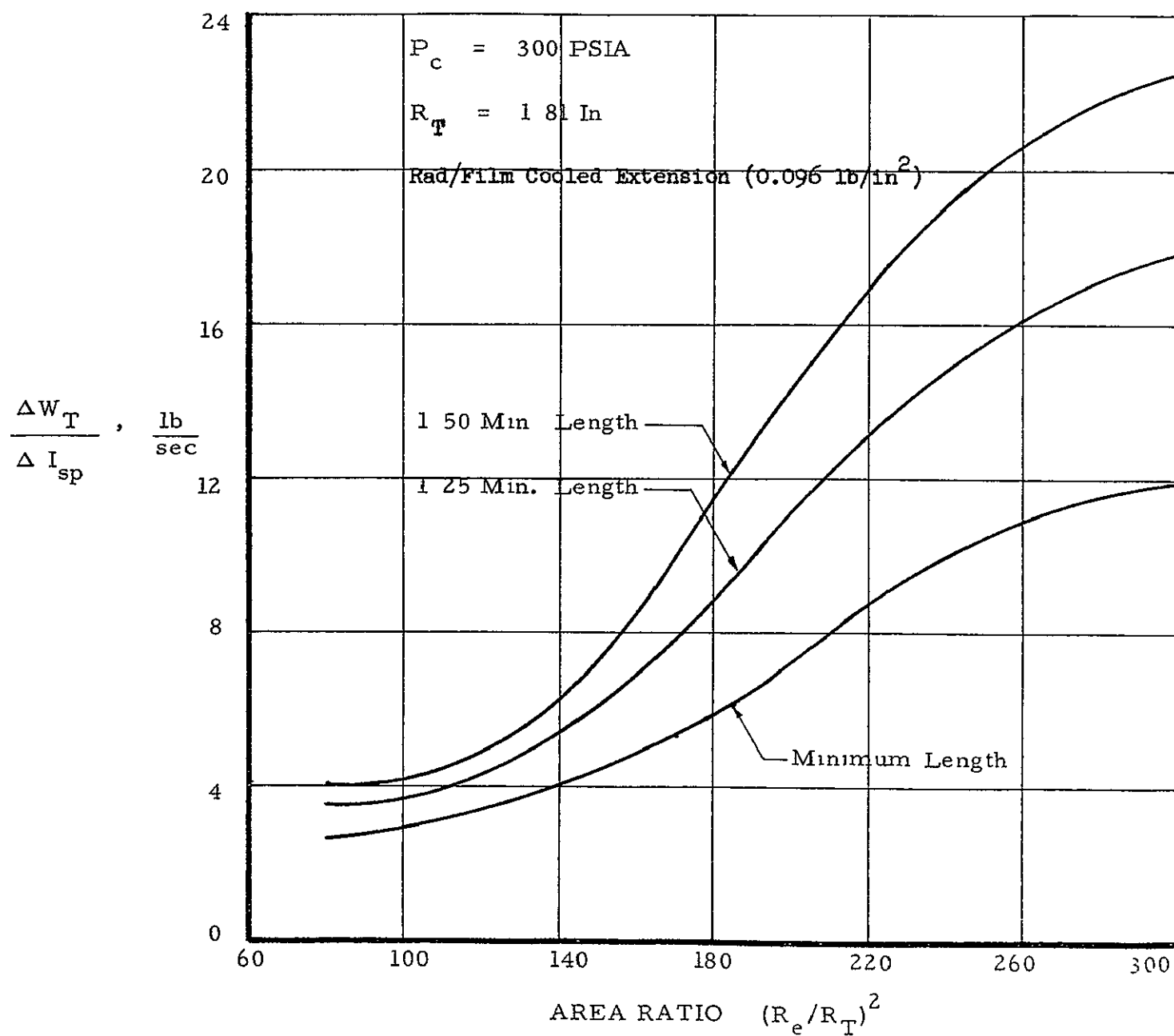Figure 30
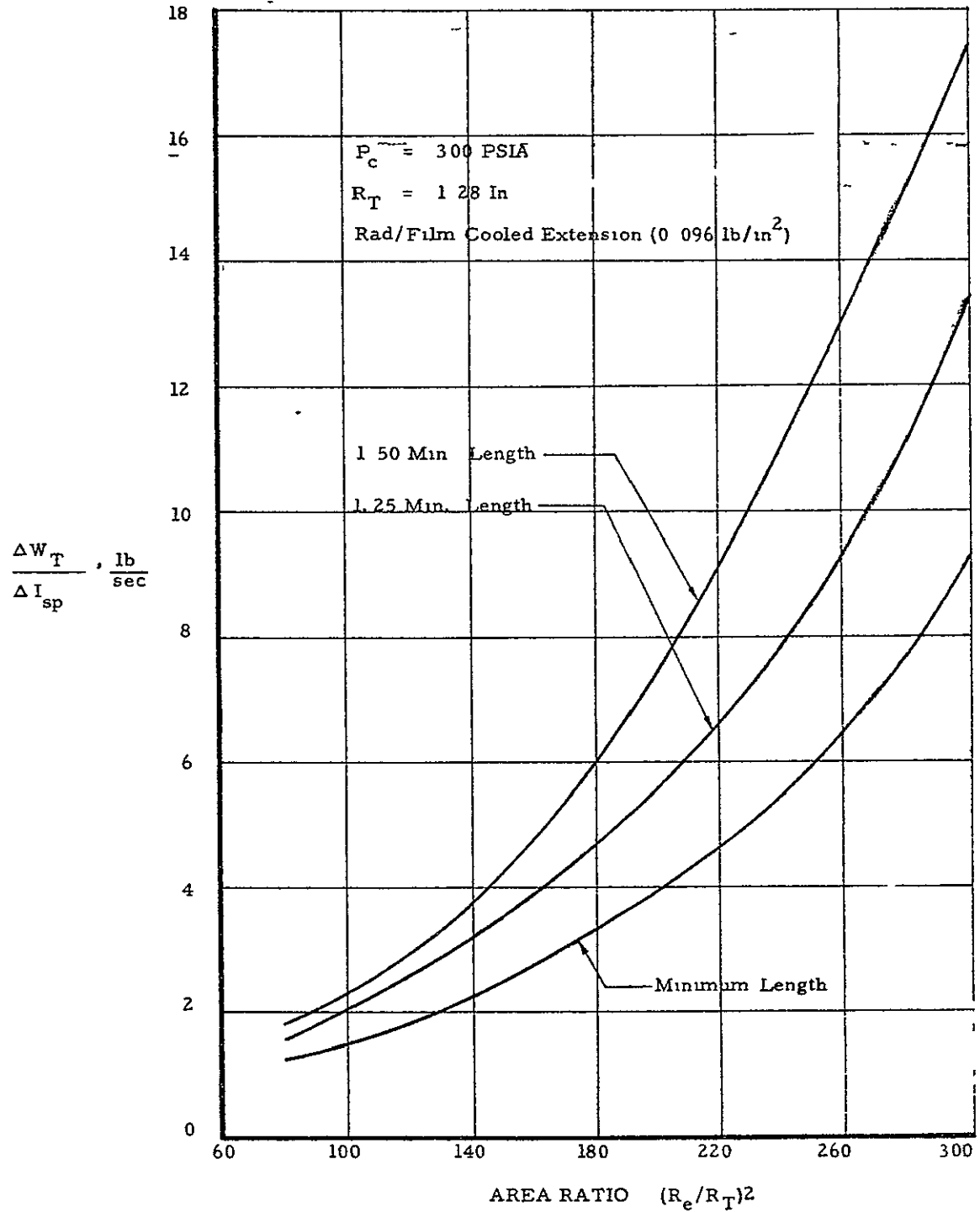
TRADE-OFF RATIO VS AREA RATIO
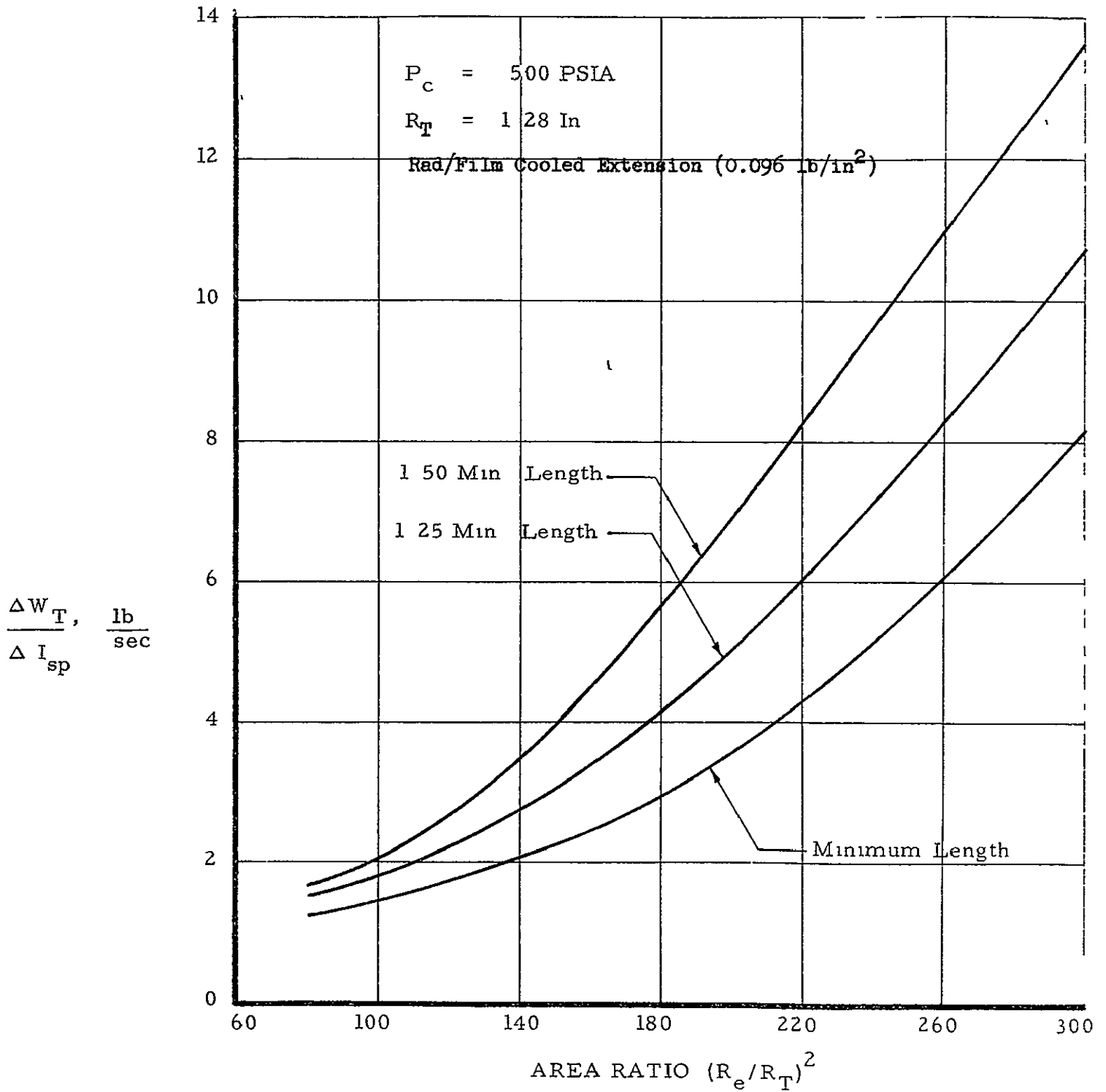
Figure 31

TRADE-OFF RATIO VS AREA RATIO
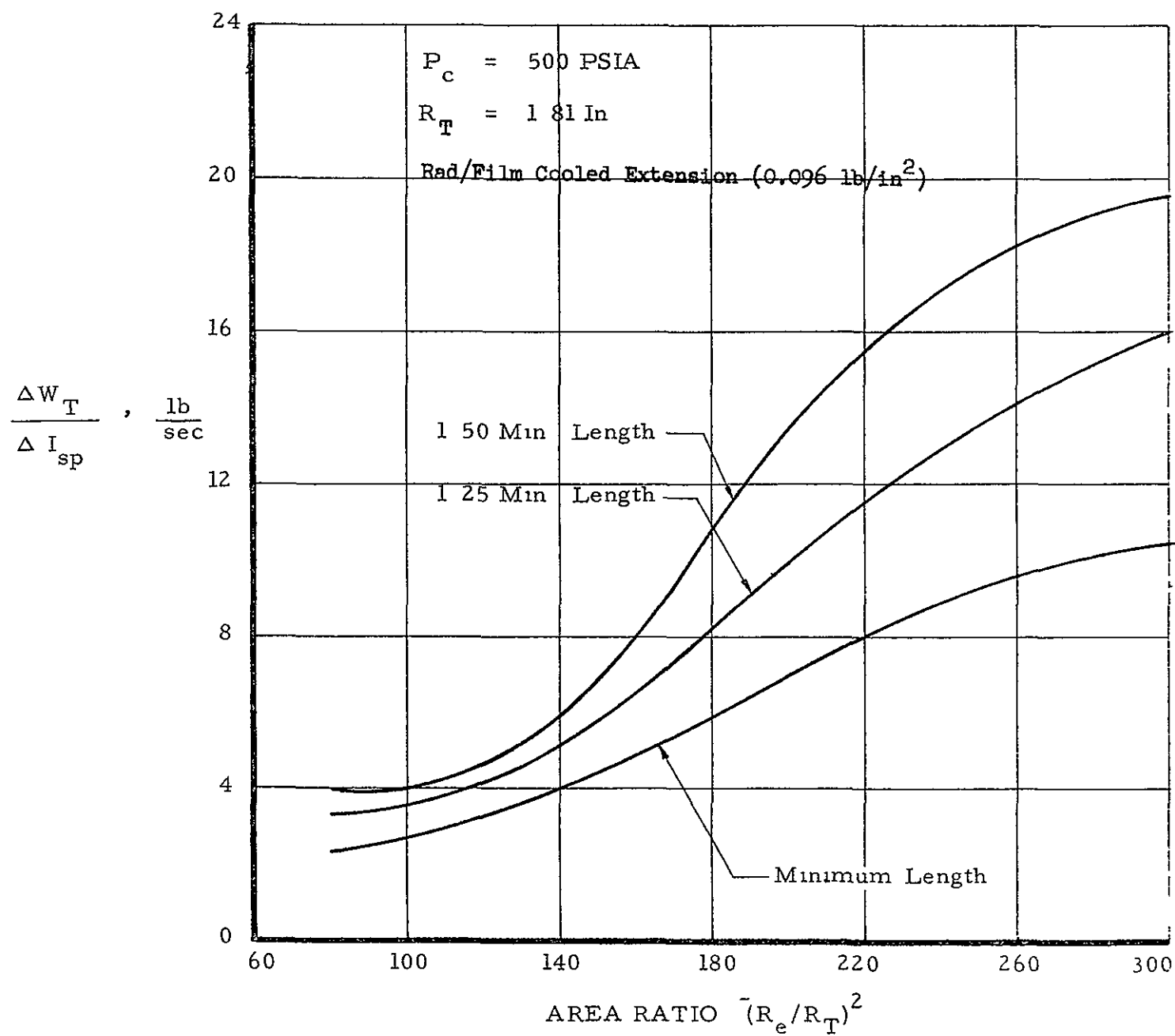(P$_c$ = 500 PSIA, R$_T$ = 1 28)

Figure 32

TRADE-OFF RATIO VS AREA RATIO
(P_C = 1000 PSIA, R_T = 1 28)

Figure 33

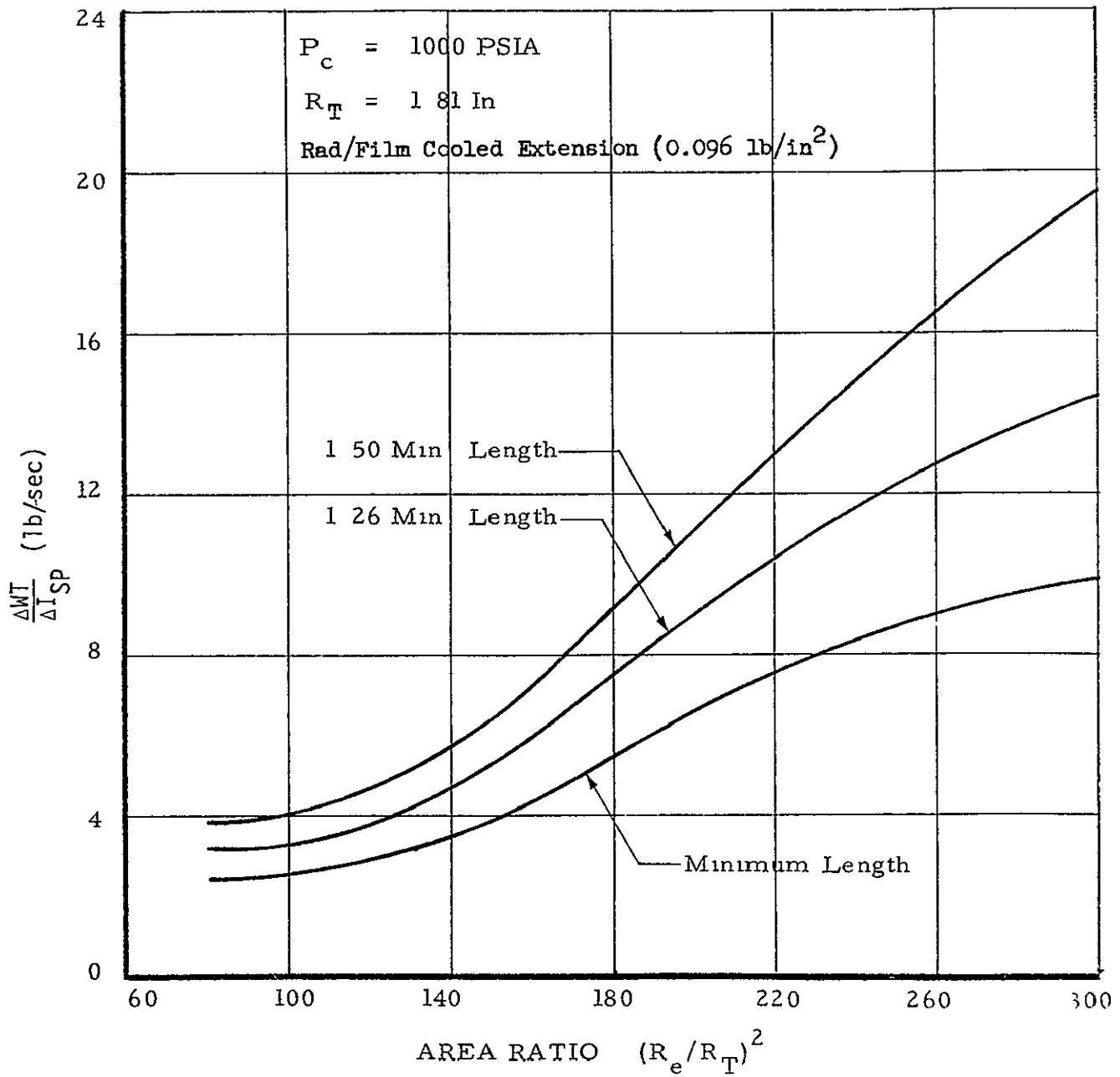$$\frac{\Delta W_T}{\Delta I_{sp}} \ , \ \frac{lb}{sec}$$

$P_C = 300 \ PSIA$

$R_T = 1 \ 81 \ In$

Rad/Film Cooled Extension (0.096 lb/in^2)

1 50 Min Length

1 25 Min. Length

Minimum Length

AREA RATIO $(R_e/R_T)^2$

TRADE-OFF RATIO VS AREA RATIO
$(P_C = 300 \ PSIA, \ R_T = 1 \ 81)$

Figure 34

P_c = 500 PSIA

R_T = 1 81 In

Rad/Film Cooled Extension (0.096 lb/in^2)

1 50 Min Length

1 25 Min Length

Minimum Length

$\dfrac{\Delta W_T}{\Delta I_{sp}}$, $\dfrac{lb}{sec}$

AREA RATIO $\overline{(R_e/R_T)}^2$

TRADE-OFF RATIO VS AREA RATIO
(P_c = 500 PSIA, R_T = 1 81)

Figure 35

TRADE-OFF RATIO VS AREA RATIO
(P_c = 1000 PSIA, R_T = 1 81)
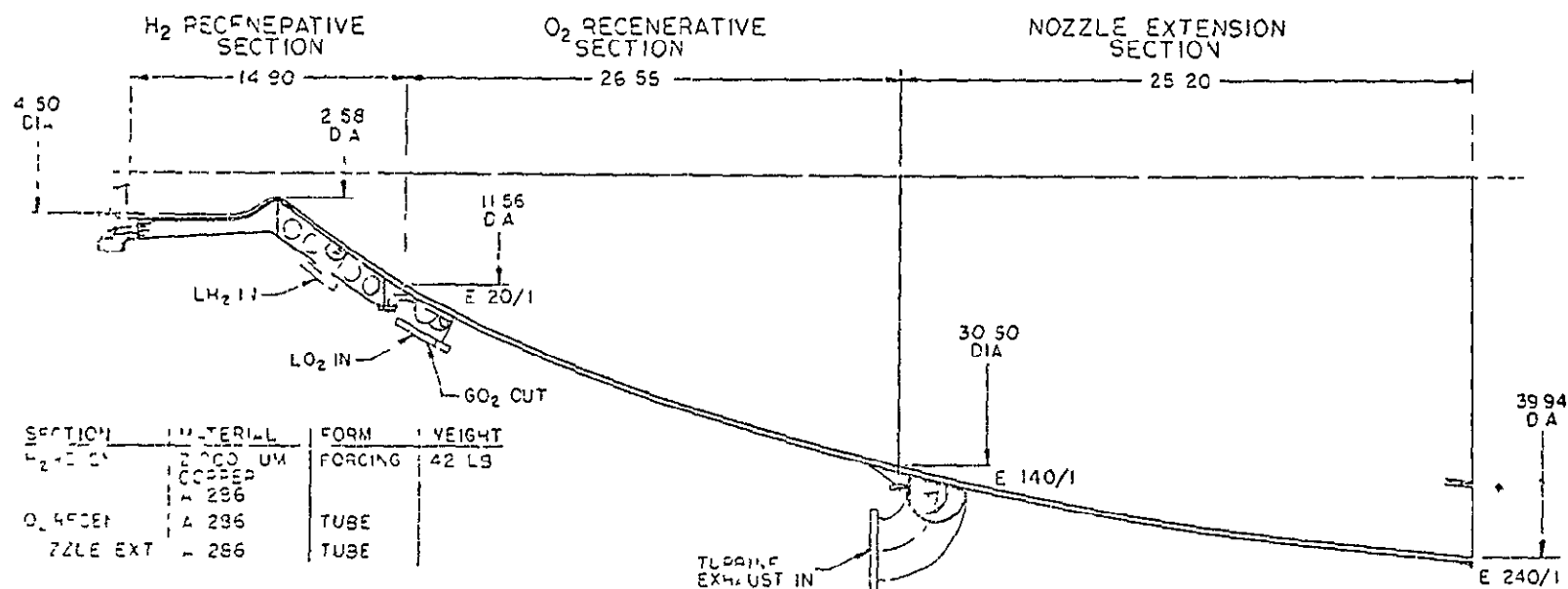
Figure 36

Figure 37
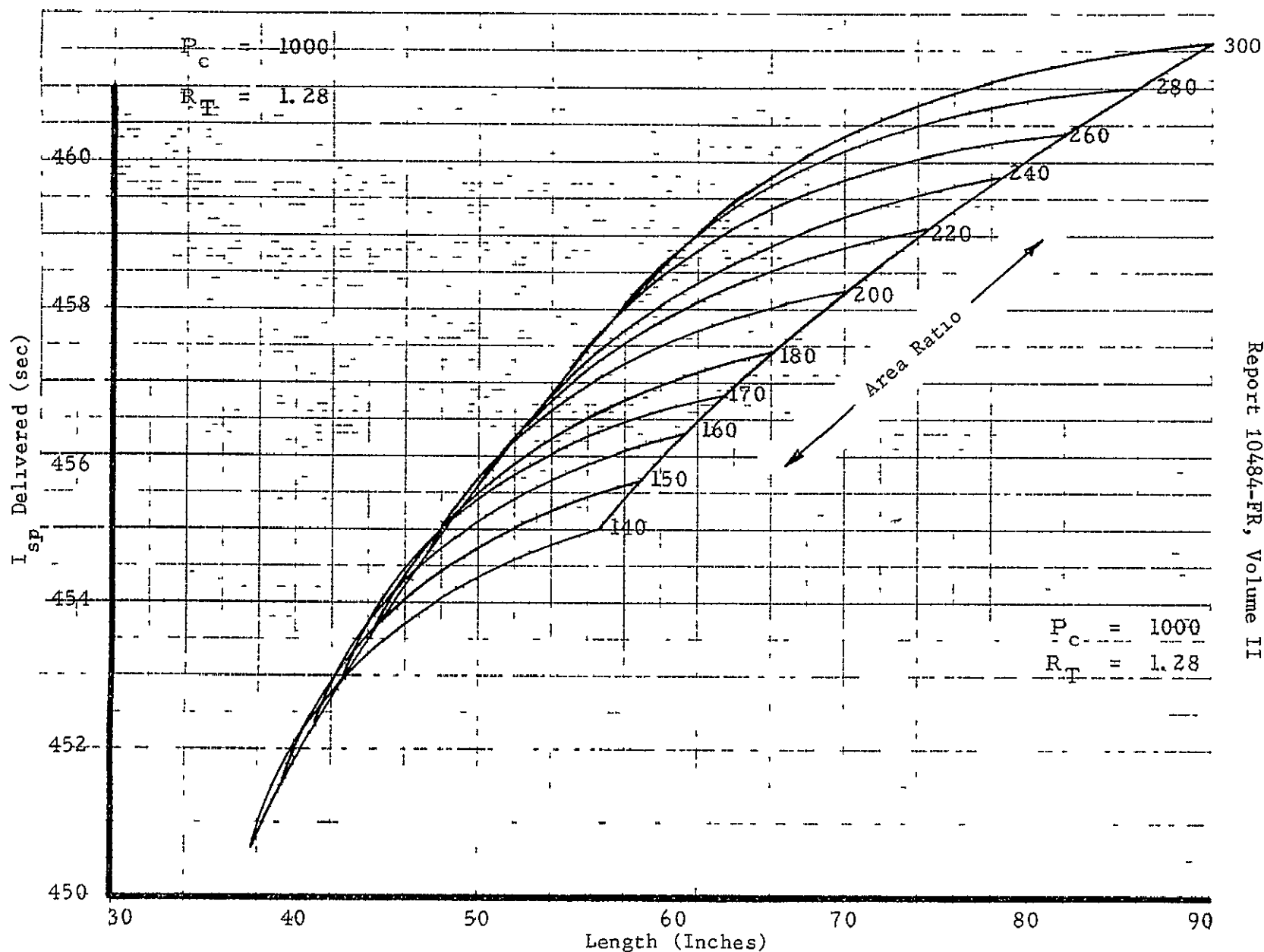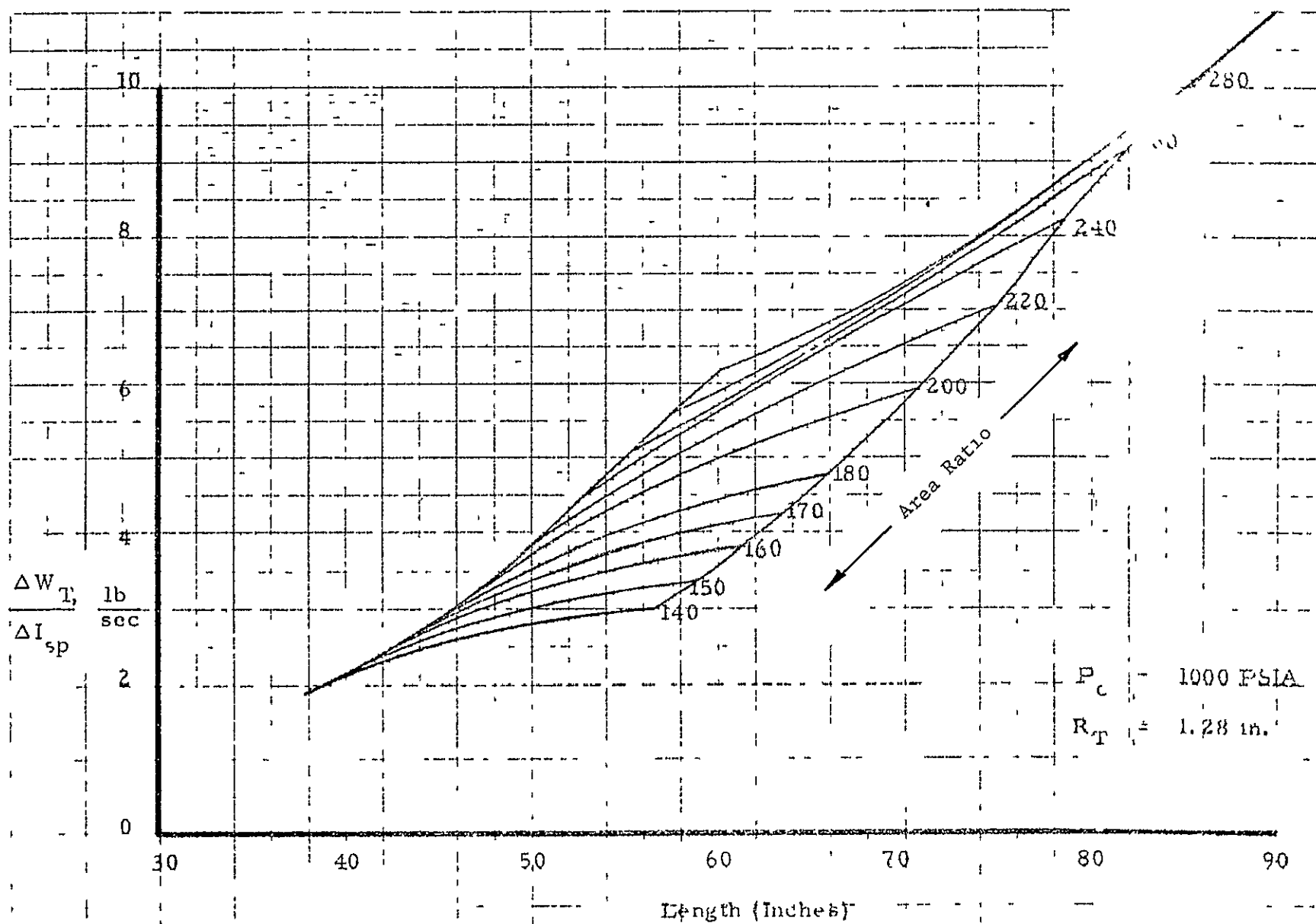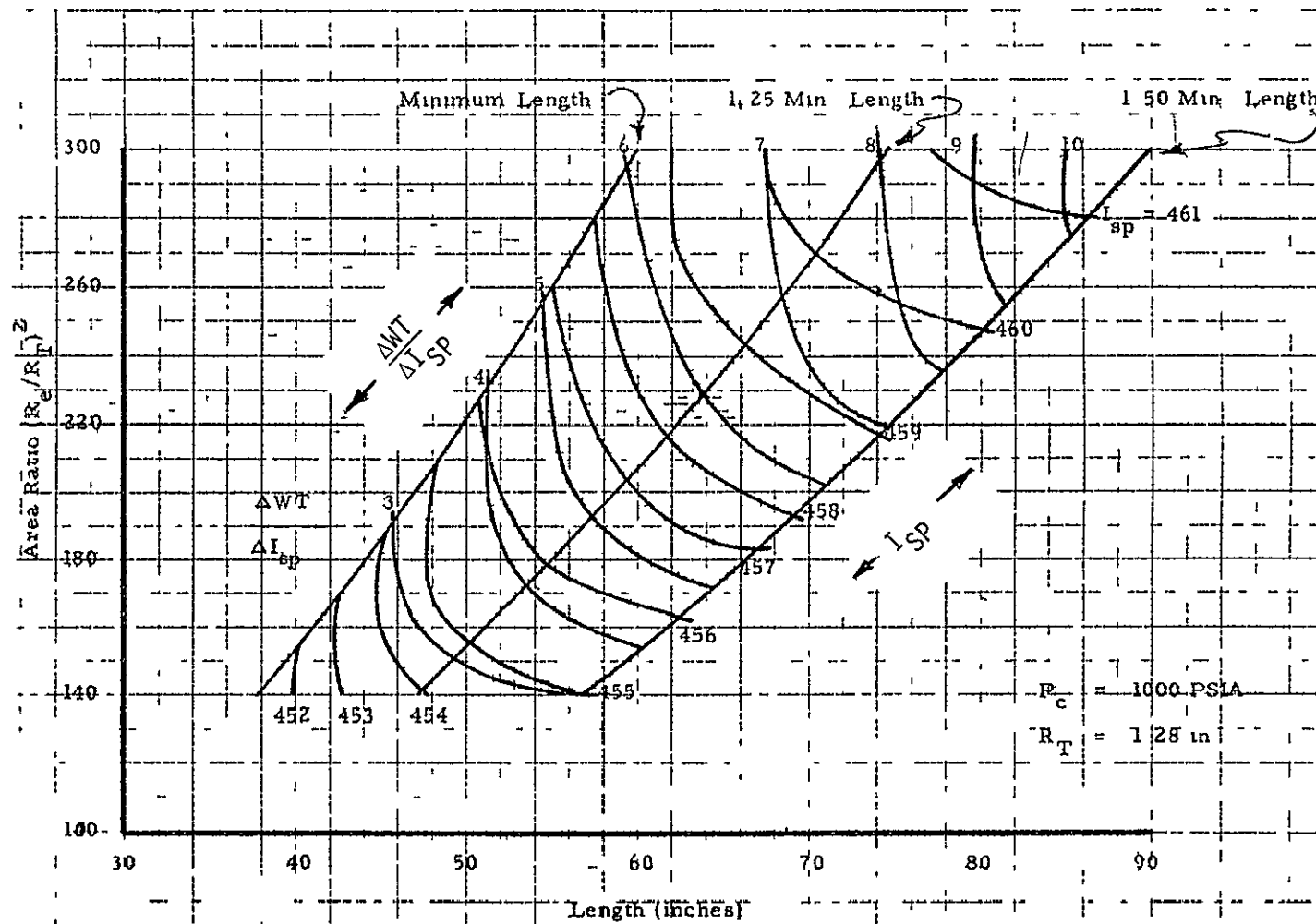
PERFORMANCE STUDY BASE CASE DESIGN

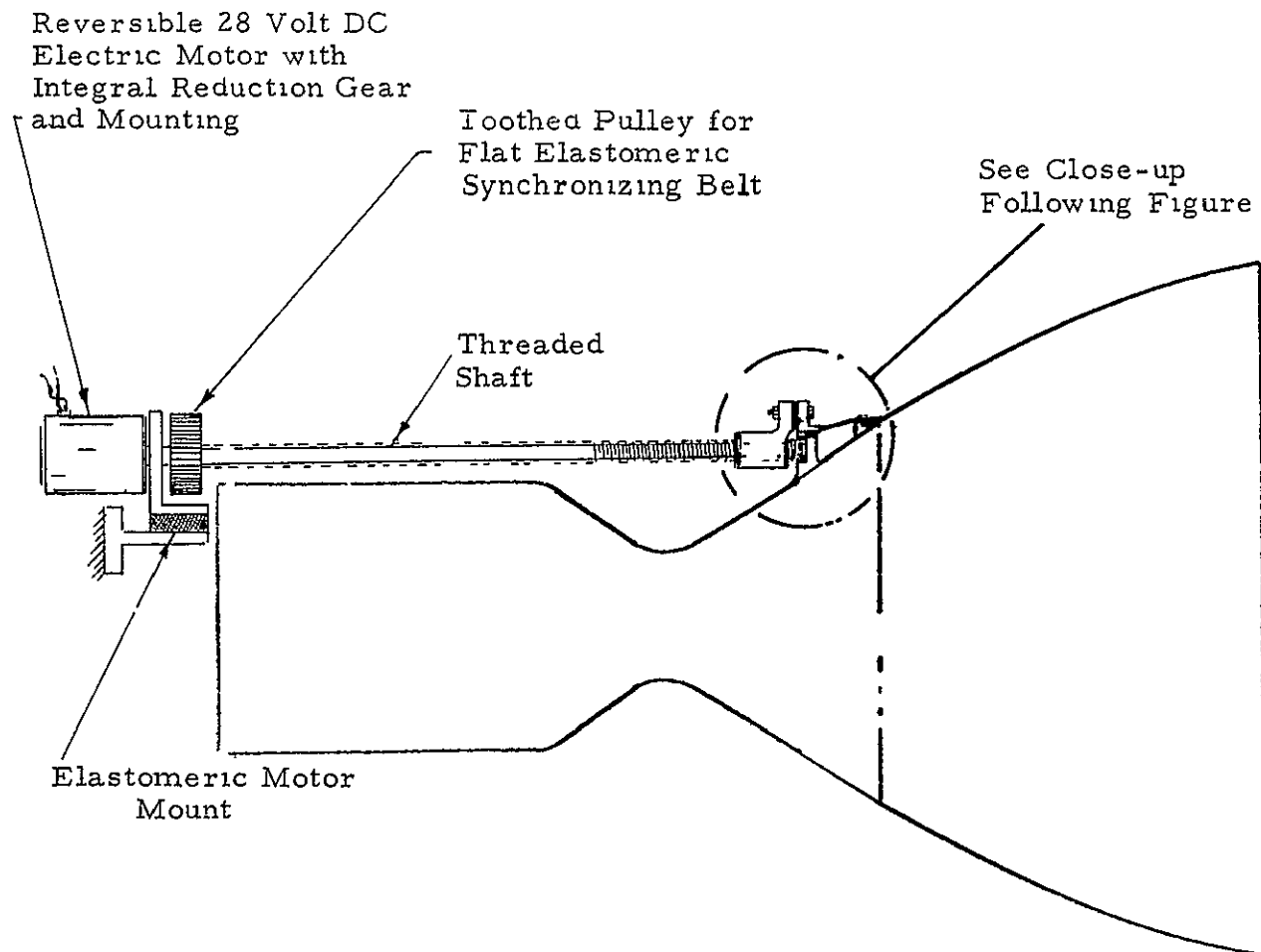I_{sp} DELIVERED vs LENGTH, WITH LINES OF CONSTANT AREA RATIO

Figure 38

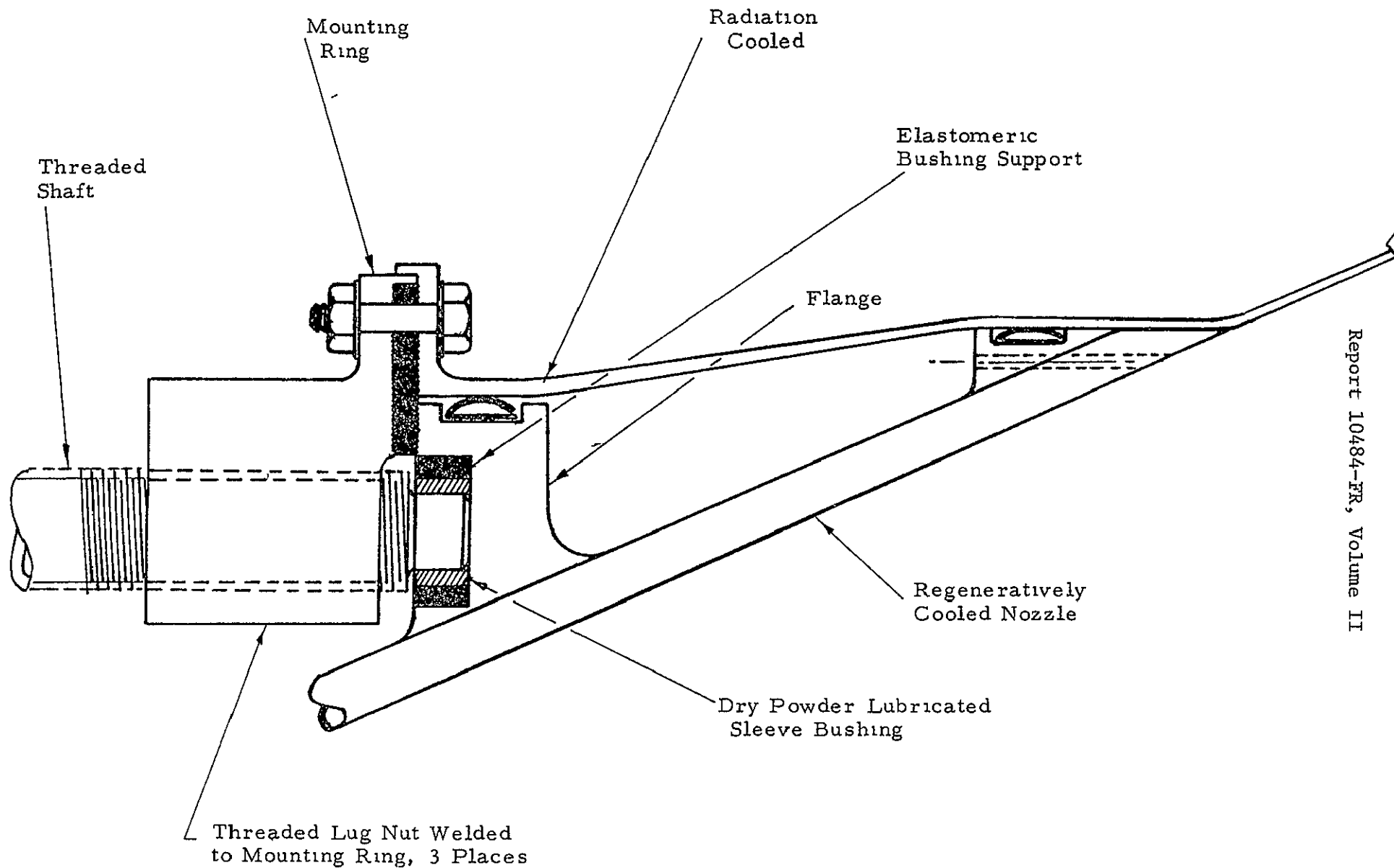$\Delta WT/\Delta I_{SP}$ VS LENGTH WITH LINES OF CONSTANT AREA RATIO

Figure 39

AREA RATIO VS LENGTH, WITH LINES OF CONSTANT
I_{SP} AND $\Delta WT/I_{SP}$

Figure 40

Reversible 28 Volt DC
Electric Motor with
Integral Reduction Gear
and Mounting

Toothed Pulley for
Flat Elastomeric
Synchronizing Belt

See Close-up
Following Figure

Threaded
Shaft

Elastomeric Motor
Mount

Figure 41

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RECOMMENDED EXTENSION TRANSLATION SYSTEM

Threaded
Shaft

Mounting
Ring

Radiation
Cooled

Elastomeric
Bushing Support

Flange

Threaded Lug Nut Welded
to Mounting Ring, 3 Places

Dry Powder Lubricated
Sleeve Bushing

Regeneratively
Cooled Nozzle

Figure 42

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RECOMMENDED TRANSLATION SYSTEM DETAIL